environment

Human **health** & Global **climate change**

A Review of Potential Impacts in the United States

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

At the dawn of the twenty-first century, the population of the United States as a whole is one of the healthiest in the world. The socioeconomic development of the last century and a half both allowed for a vast improvement in sanitation and nutrition, and provided resources for the development and maintenance of a generally effective public health system. While current health concerns in this country revolve largely around lifestyle factors such as diet, alcohol use, and physical inactivity, climate change raises the possibility that environmental factors — including higher temperatures and increased occurrence of infectious diseases — could become a growing problem.

"Human Health and Global Climate Change" is the sixth in a series of Pew Center reports evaluating the potential impacts of climate change on the U.S. environment and society. The report finds that, in general, the United States should have sufficient resources to limit climate change impacts on human health over this century. At the same time, because the linkages between climate and human health are often complex and not well defined, it is difficult to predict exactly how climate change will impact human health in the United States. Nevertheless, there are some important findings worthy of our attention:

- Higher temperatures are likely to negatively affect health by exacerbating air pollution and increasing the occurrence of heat waves. The elderly, infirm, and poor are most at risk because these conditions can exacerbate pre-existing disease. Lack of access to air conditioning increases the risk of heat-related illness.

- While there is some indication that changing climatic conditions may increase the risk of vector- and water-borne diseases, sanitation and public health system infrastructures in the United States should prevent these diseases from becoming widespread. To prevent such outbreaks, it is vital that we take steps to maintain and strengthen these infrastructures, including increased surveillance and vector control. At the same time, global health impacts from infectious diseases will almost certainly be greater, as many countries lack either the resources and/or infrastructures to protect their populations.

- Uncertainty about adverse health effects should not be interpreted as certainty of no adverse health effects. Moreover, the potential for unexpected events — e.g., sudden changes in climate or the emergence of new diseases — cannot be ruled out.

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Executive Summary

The population of the United States is among the healthiest in the world, although there are disparities in life expectancy, infant mortality, and other indices of health among different groups within the U.S. population. The main determinants of disease-related mortality in the United States today are lifestyle factors — tobacco use, alcohol use, dietary intake of calories and fats, sexual behavior, and physical inactivity. The national level of economic and social development in this country has generally provided resources to address critical health determinants such as nutrition, sanitation, and housing quality. In addition, the United States devotes a large amount of resources to health care and maintains a relatively effective public health infrastructure.

This report on the effects of climate change on human health in the United States finds that the complexity of the pathways by which climate affects health represents a major obstacle to predicting how, when, where, and to what extent global climate change may influence human well-being. Some linkages are strong and clearly defined, whereas other important connections are made difficult to define by being variable, region-specific, or mediated through multiple intervening steps.

Mortality from heat waves has been predicted to increase under most scenarios of climate change. The degree to which heat-related mortality rates increase will be determined by the ability to implement early warning systems and other interventions that focus on at-risk populations, as well as by the frequency of extreme heat waves and the changes in daytime temperature variation under future climate regimes. It is less clear whether warmer winter temperatures will result in a significant decline in wintertime mortality from cardiovascular disease.

If extreme precipitation events become more frequent, and sanitation and water-treatment infrastructure is not maintained or improved, an increase in water-borne infections may result. People are also at risk of injury or death from exposure to extreme climate events such as floods, hurricanes, and tornadoes. The public health burden of such events, however, partly depends on the ability to anticipate them, and the education and emergency response planning that may reduce impacts. In addition, current climate models are not able to confidently predict the future frequency of such events, although there has been a trend toward heavier precipitation events during the twentieth century.

Global climate change may affect human respiratory health by changing levels of air pollutants and pollens. For the United States, impacts of climate change on tropospheric, i.e., ground-level, ozone are both more certain and likely to be more important than impacts on other air pollutants. This is due to the importance of temperature in the formation of ozone as well as the large areas of the country currently affected by ozone levels exceeding national standards. Nonetheless, to date, no published studies have modeled the health impacts in the United States due to climate change effects on air pollutants.

In the United States, improved housing, sanitation, and public health interventions have controlled most of the infectious disease risks that are felt to be most climate sensitive (e.g., dengue, malaria, cholera). Of greatest concern are insect vector-borne infections that may increase as the result of changing climate. However, the multiple determinants of vector-borne disease risk and the complexity of transmission dynamics make estimating future patterns of disease difficult. In addition to climate, the risk of many vector-borne diseases is linked to lifestyle, hygiene, housing construction, trash removal, and a host of other socially- and economically-based factors. Thus, infectious disease risk may increase or decrease with climate change, depending upon the interplay of the above factors within a specific region.

For the United States, the success of public health interventions in eradicating malaria and other vector-borne diseases early in the twentieth century underscores the importance of continued public health surveillance and prevention in protecting the U.S. population from any climate-induced enhancement in vector-borne disease transmission. Maintenance and strengthening of public health infrastructure, especially surveillance and vector control, will be critical to preventing significant outbreaks in the future. Inclusion of public health and climate change experts in planning regarding land-use and utility infrastructure will also help assure maximal protection of public health during this upcoming period of climate change.

It is critical to keep in mind that uncertainty regarding adverse health outcomes is not the same as the certainty of no adverse outcomes. Given the potential scope and irreversibility of ecosystem changes and consequent effects on human health and society, traditional public health values would urge prudent action to prevent such changes. The possibility of relatively sudden but unpredictable consequences further raises the value of climate change mitigation for health concerns.

I. Introduction

The World Health Organization (WHO) defines health as "... a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." The WHO also recognizes that an ensemble of factors contribute to human health, including biophysical, social, economic, political, and cultural factors. These factors operate through a diversity of determinants, ranging from individual lifestyles and consumption behaviors, sexual practices, and psychosocial stressors, to workplace and environmental toxic exposures, population movements, and health care and public health interventions.

Both the WHO and the U.S. Centers for Disease Control and Prevention (CDC) have recently expressed concern that global climate change may have major impacts on human health, either by directly influencing disease patterns, or through indirect pathways involving food production, water distribution, or international economies. A number of reviews have summarized the evidence for health impacts of climate change, both globally (Watson et al., 1996; McMichael et al., 1996) and specifically for the United States (Patz et al., 2000; Smith and Tirpak, 1989).

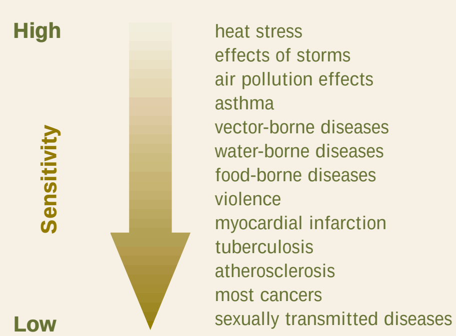
Human health may be affected by both the regional climate and the ambient weather. Climate, or the long-term (decades or longer) average weather conditions in a region, may influence diseases by determining suitable habitats for disease agents. Weather, or the short-term (minutes to days) condition of the lower atmosphere, generally affects human health through extremes of temperature, precipitation, or winds. The term "climate variability" refers to deviations from the average climate for a region over a period of weeks to years, and includes such phenomena as droughts and the El Niño Southern Oscillation (ENSO). Scientists frequently use associations of climate variability and human health to infer how climate change will affect human health.

The complexity of the pathways by which climate and weather affect health represents a major obstacle to predicting how, when, where, and to what extent global climate change may influence human well-being. Health is affected by the availability of adequate and nutritious food, ample potable water, good quality housing, and other conditions of hygiene that also are strongly influenced by forces in the environment, including the climate. Thus, exposure to infectious agents, immune responses, and extent of contagiousness may be altered under conditions of global climate change. In addition, people are at risk of injury or death from exposure to extreme climate events such as floods, hurricanes, tornadoes, and heat waves. For such exposures, increased frequency or severity of these events under climate change scenarios could produce direct and measurable impairment of physical and mental health. The magnitude of such effects, however, depends partly on the ability to anticipate them, and on the education and emergency response planning that may reduce impacts. In general, the ultimate public health burden from climate change will be determined by the balance between changes in health stressors due to climate change and adaptive measures designed to protect populations from those health stressors.

Although climate change is a global issue, this paper primarily addresses the current state of knowledge of the potential effects of climate change on human health in the United States. These effects are explained in the context of current trends in health in the United States, as well as non-climate environmental stressors that may interact with any changes brought about by a changing climate. While the focus of this paper is on health in the United States, some discussion of climate impacts on health in other countries is necessary for several reasons. First, the world is increasingly interconnected — accelerating international travel is a main factor behind the re-emergence of many infectious diseases. Many climate-sensitive diseases (Figure 1) are not widespread in the United States today, nor are they likely to become endemic in the near future. For these diseases, however, imported cases may become a more significant threat to U.S. health if climate change increases their incidence abroad. Second, global interconnections are more than conduits of diseases. Increasing economic and political links to other countries will lead to a sharing of the burdens imposed by health changes around the world. Lastly, although climate-sensitive diseases, such as malaria and cholera, are not currently prevalent in the

Figure 1

Which Diseases are Climate Sensitive?



United States, they were domestic health concerns as recently as the first half of the twentieth century. The ability to study and understand how these diseases respond to climate variability, which is crucial to assessing possible domestic resurgence in a setting of climate change, depends on an understanding of these diseases in other countries. Thus, the goal of this report is to highlight the potential public health burden for various kinds of health impacts, and identify which populations would be most at risk. This report also reviews the quality and quantity of scientific literature supporting inferences about specific health impacts, noting the relative importance of climate change for each health impact compared to other factors. While this paper focuses on potential impacts on human health, rather than possible adaptations to lessen those impacts, the authors acknowledge that the ultimate effects of climate change on the health status of the nation will be determined by future changes in society and technology.

II. Status and Determinants of Health

A. Current Status of Health in the United States

The population of the United States is among the healthiest in the world, with a life expectancy that increased from 47 years a century ago to 76.5 years in 1997 (Hoyert et al., 1999). The main causes of death in the United States vary among the different age groups, with deaths among those over 55 dominating overall mortality (Table 1). With the exception of unintentional injuries, the five leading causes of death for the population as a whole are chronic diseases with multiple causes, and are primarily determined by genetic predisposition and lifestyle factors such as diet and cigarette smoking. Climate or climate-sensitive factors may be linked to exacerbations of these chronic diseases, as when heat stress or increased air pollutants exacerbate underlying chronic pulmonary disease, but the impact of climate relative to other factors is likely to be small. Nonetheless, even a small influence, if consistent and widespread, may have a substantial public health impact given the large burden of the chronic diseases.

Current mortality in the United States from the diseases most commonly associated with climate change (see Box 1) is comparatively small and includes heat-related deaths and deaths

Table 1

Leading Cause of Death

in the United States by Age Group (1996)

Age Group	Cause of Death	Number of Deaths
1-14	Unintentional Injuries	5,580
	Malignant Neoplasms	2,561
	Congenital Anomalies	1,095
	Homicide	934
	Heart Disease	551
15-34	Unintentional Injuries	26,634
	Homicide	11,976
	Suicide	10,219
	HIV	8,461
	Malignant Neoplasms	6,477
35-54	Malignant Neoplasms	61,676
	Heart Disease	48,251
	Unintentional Injuries	24,113
	HIV	19,896
	Suicide	11,578
55 and over	Heart Disease	679,534
	Malignant Neoplasms	469,816
	Cerebrovascular Disease	150,164
	Chronic Lung Diseases	101,516
	Pneumonia and Influenza	78,592
Whole Population	Heart Disease	733,361
	Malignant Neoplasms	539,333
	Cerebrovascular Disease	159,642
	Chronic Lung Diseases	106,027
	Unintentional Injuries	94,948

Source: Adapted from CDC - National Center for Injury Prevention and Control, Leading Causes of Death Reports (http://www.cdc.gov/ncipc/osp/data.htm), accessed on May 25, 2000.

Box 1

What Makes a Human Disease Climate Sensitive?

Most human diseases have numerous causes and determinants (see Section II.C). The effect of changes in climate on any given disease depends on whether climate is itself an important determinant of the disease, or whether climate has a strong influence on any of the important determinants of the disease. Two examples of diseases for which climate itself is an important determinant are heat stress and heat stroke. Heat stress and heat stroke have relatively few non-climate determinants (see discussion below), so changes in climate are likely to have a significant effect on the occurrence and severity of these diseases. At the opposite extreme would be a disease such as colon cancer. Colon cancer has a number of determinants, including genetics and diet, that are not strongly affected by changes in climate. Thus, colon cancer would be a disease that would not be considered climate sensitive.

In between heat stress and colon cancer are a number of diseases caused or influenced by many factors, some of which are related to climate. In the case of vector-borne infectious diseases, climate factors have a strong impact on vector and disease agent reproduction and survival, but less of an impact on vector control measures, vaccines, medical treatments, travel, pesticide resistance, and other determinants of the activity of vector-borne diseases. Alternatively, climate may exacerbate or influence mortality from a chronic, multifactorial disease, such as chronic obstructive lung disease or coronary artery disease, without having much of an effect on the original causes of the disease. In this case, the stress of extreme temperatures can lead to exacerbation of the diseases, but the original causes of the diseases involve lifestyle factors and genetics, which are not significantly influenced by climate.

Thus, for complex, multifactorial diseases such as vector-borne infectious diseases and respiratory diseases, the ultimate impact of climate change will depend not only on the extent of regional changes in climate and climate variability, but also on changes in the many other factors involved in the disease. For example, climate-induced increases in mosquito populations will be much more likely to have an effect on vector-borne diseases if there is a coincident increase in pesticide resistance, making vector control more difficult. In general, the more factors involved in the causation of a disease, and the more complex the interrelationships, the more difficult it is to predict how sensitive that disease will be to climate change.

from vector-borne and water-borne diseases. There were an average of 175 deaths annually from weather-related heat stress between the years 1979 and 1995 (CDC, 1997b). Reported cases of climate-sensitive vector-borne and other infectious diseases in the United States are summarized in Table 2.

While the United States as a whole enjoys excellent health, there are disparities in life expectancy, infant mortality, and other indices of health among different groups within the population. Life expectancy in 1997 ranged from 67.2 years for black males to 79.9 years for white females (Hoyert et al., 1999).

Table 2

Reported Cases of Potentially Climate-sensitive Diseases in the United States (1997)

Vector-borne Diseases	Number of reported cases
Malaria	2,001
Dengue	56 imported; 3 acquired in U.S.
Lyme Disease	12,801
Arboviral Encephalitis	
La Crosse	127
St. Louis	13
Eastern Equine	14
Other infectious diseases	
Hantavirus	21
Cryptosporidiosis (45 states)	2,566
Cholera	6

Source: Adapted from CDC (1997a).

Death rates from cardiovascular disease among those 25 to 64 years old were about 2.4 to 2.9 times higher in persons earning less than $10,000 annually than in those earning more than $15,000 annually (National Center for Health Statistics, 1998). It is likely that multiple risk factors for climate-related health effects will occur together in specific populations. For example, advanced age, underlying pulmonary disease, and lack of air conditioning at home — all risk factors for heat-related mortality — may all be present in high frequencies among the urban poor population.

B. Global Health

To more fully understand the current status of health in the United States, especially with respect to climate-sensitive diseases, it is instructive to compare the United States to other parts of the world. The current story of global health is one of contrasts. Whereas chronic, noninfectious diseases account for the vast majority of deaths in the developed world, climate-sensitive infectious diseases are among the leading causes of death in the developing world (Table 3). Worldwide, life expectancy varies widely, ranging from 79.7 years in Japan to 40 years in Sierra Leone in 1995 (WHO, 1996). When the burden of disease is measured by disability-adjusted life years (DALYs) lost (i.e., years of life lost due to premature death and/or spent living with a disability of specified severity and duration) instead of absolute mortality, the contrast between causes becomes more apparent. Of the seven leading causes of DALYs lost in the developing world, five are infectious diseases; conversely, none of the top ten causes of DALYs lost in the developed world are infectious diseases (Murray and Lopez, 1996b). This difference in disease burden reflects a number of socioeconomic factors relevant to vulnerability to climate change, as discussed briefly in the next section.

Table 3

Leading Causes of Death
in the Developed vs. the Developing World

Developed World	Developing World
1. Ischemic heart disease	1. Lower respiratory infections
2. Cerebrovascular disease	2. Ischemic heart disease
3. Lower respiratory cancer	3. Cerebrovascular disease
4. Lower respiratory infections	4. Diarrheal diseases
5. Chronic obstructive pulmonary disease	5. Conditions arising during the perinatal period
6. Colorectal cancer	6. Tuberculosis
7. Stomach cancer	7. Chronic obstructive pulmonary disease
8. Road traffic accidents	8. Measles
9. Self-inflicted injuries	9. Malaria
10. Diabetes mellitus	10. Road traffic accidents

Source: Adapted from Murray and Lopez (1996a), p. 179.

C. Main Determinants of Human Health

To understand in a comprehensive fashion how global climate change may impact human health, one must consider climate change impacts on the wide range of health determinants. The determinants of human health are traditionally divided into host (i.e., specific to the individual) and environmental (i.e., external to the individual) factors. Important host factors include nutrition, age, underlying disease, genetic factors, and immune status. Environmental factors are many, and include quality of housing, access to sanitary facilities and clean water, and air and food that are free from chemical contamination. Additional determinants, representing an interaction of environment and host, could include psychological stress, access to preventive and curative health services, and behavioral or "lifestyle" choices. Historically, the greatest improvement in human health in the Western world was seen during the marked period of socioeconomic development that occurred between the mid-nineteenth and mid-twentieth centuries. This change has been attributed to improvements in host and environmental factors related to greater wealth, including better nutrition, improved shelter and decreased urban crowding, improved working conditions, and improvements in sanitation (Tyler and Warren, 1998). During this time, premature mortality from infectious diseases such as tuberculosis, cholera, typhoid fever, and malaria dropped dramatically in the United States. The link between economic growth and health is evidenced by the fact that changes in per capita national income have accounted for up to 25 percent of improvements in life expectancy (Tyler and Warren, 1998).

The division between environmental and host factors has been helpful in thinking about non-communicable diseases that do not involve infectious microbes. For infectious diseases, however, a third category termed "agent" factors is usually considered to represent the added characteristics of the infectious agent (Webber, 1996). These characteristics may include differences in transmissibility, ability to cause clinical disease, ability to invade specific tissues, and host specificity of various parasite strains.

The main determinants of disease-related mortality in the United States today are lifestyle factors — tobacco use, alcohol use, dietary intake of calories and fats, sexual behavior, and physical inactivity (National Center for Health Statistics, 1998). The national level of economic and social development in this country has generally provided resources to effectively address critical health determinants such as nutrition, sanitation, and housing quality. In addition, the United States devotes a large amount of resources to health care and maintains an effective, if not optimal, public health infrastructure.

In contrast, the two greatest risk factors for disease in the developing world are malnutrition and unsafe water (Murray and Lopez, 1996a). Their estimated combined contribution to overall global mortality in 1990 was 17 percent of all deaths, and for some regions of the world, they account for a far greater health burden. For example, while malnutrition was insignificant as a cause of death in the Established Market Economies,[1] it caused 32 percent of the deaths in sub-Saharan Africa and more than 18 percent of all deaths in India. Similarly, poor water quality accounted for far less than 1 percent of the deaths in the Established Market Economies, but nearly 11 percent of deaths in sub-Saharan Africa and 9 percent of deaths in India (Murray and Lopez, 1996b). In general, climate change is more likely to have an impact on areas that currently have difficulty controlling diseases that are felt to be more climate sensitive, such as vector- and water-borne infectious diseases. Similarly, any possible declines in food production will have a far greater effect if they occur in parts of the world currently experiencing hunger and malnutrition. Thus, this contrast in disease determinants suggests that the United States should be less vulnerable to the health impacts of climate change than much of the developing world.

D. Environmental Trends in the United States

Climate is only one of many factors influenced by humans that affect the environment and ultimately human health. Contaminants released to air, water, and soil, and alteration of vegetation and other land surfaces have had and continue to have profound influences on local ecosystems and human health in the United States and worldwide.

Emissions of air pollutants, particularly the six criteria air pollutants,[2] have had direct negative impacts on human health. U.S. outdoor air quality, as measured by monitoring stations, has generally improved since the late 1960s and early 1970s. Since the Clean Air Act of 1970, the levels of these six criteria air pollutants have tended to decrease (U.S. EPA, 1996a). Levels of some pollutants, however, such as the ozone precursor nitrogen dioxide, have not decreased significantly. Forecasts for emissions of the six criteria air pollutants through 2010 show stabilization at current amounts, except for a 5 to 10 percent increase in particulate matter measuring less than 10 microns (PM_{10}) (U.S. EPA, 1996a).

In contrast to air quality, trends in water quality are harder to ascertain. The most recent U.S. Environmental Protection Agency (EPA) report on national water quality noted that 36 percent of the surveyed miles of streams and rivers and 38 percent of the estuarine area surveyed were considered impaired (U.S. EPA, 1998). The main causes of this impairment were nutrients and bacteria for both types of surface water. Rivers were also impaired by siltation, and estuaries were also impaired by toxic organic chemicals. Groundwater supplies have not been as thoroughly monitored as surface waters. Most measurements have focused on chemical pollutants such as nitrates and pesticides, and only three states reported to the EPA in 1996 about levels of bacteria in groundwater (U.S. EPA, 1998). Nonetheless, recent studies suggest moderately frequent contamination of groundwater supplies with a variety of intestinal viruses (Abbaszadegan et al., 1999). The extent of microbial contamination of U.S. water supplies is a critical factor for determining the impacts of climate change on water-borne infectious diseases. In addition to quality, though, the quantity of available, clean water for both irrigation and direct consumption is also essential for maintaining health in the United States.

III. Discussion of Health Impacts of Climate Change in the United States

Weather and climate variability (see Box 2) can affect human health through direct and indirect mechanisms. Direct effects involve mostly physical impacts that act to cause physiologic stress (e.g., temperature) or bodily injury (e.g., storms, floods). Direct effects tend to be observed soon after the causative weather event, and are generally more easily modeled and understood than indirect effects. On the other hand, indirect effects, such as climate impacts on food supplies and the outbreak of vector-borne diseases, may operate through diverse pathways involving multiple variables. These more complex mechanisms may demonstrate a threshold or nonlinear response to increasing levels of a climate factor.

The complexity of these health effects leads health impact assessments to focus on partial mechanisms — or pieces of the full causal chain — in discussing how climate change may affect human health. Moving from analyzing these partial mechanisms to being able to predict incidence of human disease for a specific location is a huge step. One critical question, often unanswerable for a complex system that links climate to health outcomes, is whether the most significant factors in the causal chain have been identified, measured, and evaluated. This section attempts to identify the extent to which the critical factors for a given disease are identified and measurable, the level of confidence regarding how climate change will affect that disease, and who will most likely be affected. In addition, consideration of all relevant factors, including actions taken to adapt to climate change impacts, is required to assess climate *vulnerability* as opposed to climate *sensitivity*. A health problem may be climate sensitive if its severity responds in some way to changes or variation in climate. Whether or not those changes translate into measurable effects on a population, however, depends on the ability of that population to adapt or otherwise protect itself against the increased threat. As an example, heat-associated mortality in New York City is sensitive to changes in climate. The vulnerability of two separate populations, one in a wealthy area of Manhattan, for example, and the other in a poor area of the Bronx, will be very different. The wealthy population is likely to have better access to air conditioning and more of an indoor lifestyle, while

Box 2

Climate Variability versus Climate Change

Most observations of the relation between health and climate are based on climate variability (i.e., short-term variations in patterns of weather and climate). On a day-to-day, month-to-month, and even year-to-year basis, climatic conditions change a great deal more than they do on a decade-to-decade basis, and even more than is predicted with greenhouse-gas-induced climate change. Aspects of this short-term variability (such as periods of unusual nighttime minimum or daytime maximum temperatures, unusually warm summers or snowy winters, or droughts spanning several seasons) are most noticeable to the general population, and have most commonly been associated with effects on human health. Longer-term climate change can only be detected by reviewing long-term data records. In assessing the health impacts of long-term climate change, a distinction must be made between health effects that are influenced by short-term climate variability and health effects that may be influenced by long-term changes in climate regimes. For example, the understanding of interactions between temperature and rainfall and specific diseases, such as dengue or Lyme disease, is based on studies done on effects of variable short-term climate in a setting of stable long-term climate. For these vector-borne diseases, the important question is whether, in addition to any effects of shorter-term climate variability, prolonged climate change will alter the abundance and behaviors of the various animal species that sustain these diseases. Such changes, which may be hard to predict due to the unprecedented nature of climate change, may lead to increases or decreases in disease activity.

Examples of health impacts that are primarily associated with climate variability include respiratory effects from air pollutants and health impacts related to extreme weather events. Heat-related mortality is another example of a health impact that is primarily related to climate variability. Studies of future heat-related mortality in a setting of climate change have generally applied predicted mean temperature increases to current patterns of variability. Heat-related mortality is partly related to daytime maximum temperatures exceeding a physiologic threshold. Thus, applying a fixed temperature increase to current patterns of variability leads to a higher frequency of days exceeding a given threshold, and therefore greater estimates of heat related mortality. To the extent that future climate variability on a scale of days to months changes, these estimates will be incorrect. Should climate variability decrease, days exceeding a given threshold would also decrease, leading to less of a change in heat-related mortality. On the other hand, should climate variability increase, this increase in variability combined with an increase in average temperatures would lead to a marked increase in days exceeding a given threshold. This effect becomes more complicated, though, when one considers the effects of daily variation in temperature. Specifically, climate change is expected to warm nighttime temperatures more than daytime temperatures, thus decreasing the daily temperature variation. Since heat-related mortality is also associated with elevated nighttime minimum temperatures, a decrease in the daily variability of temperatures could also increase the risk of heat-related mortality.

the poorer population, particularly the elderly poor, is likely to have less access to air conditioning, and is therefore more vulnerable to the changes in heat stress. While this section discusses the factors that account for population vulnerability, a full consideration of all adaptive measures is beyond the scope of this work. The role of adaptation in responding to climate change will be explored more fully in future Pew Center reports.

A. Direct Health Effects

Temperature Extremes, Heat-related Deaths, and Winter Mortality

Well-publicized death tolls from heat waves in 1995, 1998, and 1999 have focused public attention on the effects of warmer temperatures on human health. During hot weather, perspiration evaporates from the skin, which cools the body and maintains an acceptable body temperature for physiologic functions. Beyond certain heat extremes, however, the body is unable to cool itself, and the normal biochemical processes that allow life shut down. The precise weather conditions under which the body fails to maintain normal function, however, vary depending on age, presence of heart or lung disease, ability to maintain hydration, and other health conditions. In addition, continued exposure to warm temperatures leads to acclimatization, a physiologic change in the body that allows it to adapt to the increased warmth.

The lethality of a heat wave is enhanced by its occurrence early in the summer (before populations have had a chance to acclimate), by long duration, and by higher nighttime minimum temperatures (Ramlow and Kuller, 1990). This last factor is important because increased greenhouse-gas-induced climate change is expected to have a greater effect on nighttime temperatures, as the heat trapping effect of the greenhouse gases (GHGs) prevents radiative nighttime cooling of the earth. This climate change effect will also be exacerbated in cities by the "urban heat island effect," which involves the nighttime release of heat stored during the day in cement and metal urban materials. Heat-wave-related mortality is greatest among infants and the very old, especially those with underlying diseases. The highest risk among these groups is associated with urban isolation and lack of access to air conditioning (Semenza et al., 1996; Kilbourne et al., 1982).

Kalkstein and Greene (1997) made predictions of heat wave-related mortality for 44 U.S. cities based on climate scenarios for 2020. Changes in mortality range from an increase of 347 deaths (181 percent) in Chicago to a decrease of 30 deaths (23 percent) in Philadelphia, depending on the general circulation model (GCM) used. These estimates assume full acclimatization, constant populations, and no change in availability of air conditioning or housing stock. They also rely on GCMs for their estimates of climate and weather variability. The ability to extrapolate from observations and the directness of the relation between temperature and human physiology lend a high degree of confidence to estimates of heat-wave-related mortality. Nonetheless, uncertainty in future climate variability and future trends in social and technological mitigating factors may render those estimates inaccurate.

At the other extreme, overexposure to cold temperatures leads to frostbite and death, as the body is unable to generate enough heat to maintain normal physiologic functions. Climate change is expected to increase average winter temperatures in the United States by at least as much as the increase in average summer temperatures (Wigley, 1999). This raises several critical questions: (1) Does an increase in average winter temperatures mean a decrease in the severity and/or frequency of episodes of extreme cold?; (2) Does overall wintertime mortality increase significantly with colder temperatures?; and (3) Would warmer winter temperatures result in lower overall mortality?

Overall mortality has a clear seasonal pattern, in both temperate and sub-tropical states, with highest mortality occurring during the winter. Of note, mortality among those under 45 years of age has the opposite pattern, with a summertime peak of mortality, but this pattern is obscured by the greater number of deaths among those over 45 years old (Kilbourne, 1998). The peak in wintertime mortality is due to deaths from a number of causes, including pneumonia, influenza, cardiovascular disease, stroke, and chronic obstructive pulmonary disease (Kilbourne, 1998). The issue of how climate change will affect winter mortality is not settled. Some authors have concluded that change in climate is unlikely to affect the infectious diseases that peak in the winter (e.g., influenza), therefore little improvement in wintertime mortality is likely with a warming climate (Kalkstein, 1993). One study based on British data concluded that a substantial decrease in wintertime mortality could occur in a setting of climate change (Langford and Bentham, 1995). Conflicting results have been obtained for studies of the United States.

Martens (1997) focused on the relation between monthly average temperatures and overall mortality, with emphasis on respiratory and cardiovascular disease. His combined analysis of a number of studies on this issue revealed a consistent decrease, primarily in cardiovascular mortality, with warmer winter temperatures, and a sharper increase in mostly respiratory mortality with increasing summer temperatures. His modeling of overall changes in mortality under climate change scenarios for the United States indicated a 5.6 percent decrease in overall mortality in the over-65 population. This overall decrease was due to the decrease in the rate of cardiovascular mortality with less severe winter temperatures. Using a synoptic approach that characterized and grouped entire air masses rather than analyzing the effects of individual climate variables, Kalkstein and Greene (1997) analyzed the relation between anticipated changes in climate and wintertime mortality. Their findings suggested a more modest decrease or even an increase in wintertime mortality by 2020, depending on the GCM model, and showed an overall increase in mortality when summer and winter data were combined. It remains debatable to what extent warmer winter temperatures may decrease mortality among those with cardiovascular disease even as mortality from summertime heat waves rises among the very young and the very old.

The ultimate public health burden of changes in temperature extremes, both warm and cold, will be moderated by a number of factors. The true burden of heat-related mortality could decrease over time in a setting of climate change should social factors relieve isolation of the urban poor and provide greater access to cooled environments and should the decrease in cardiovascular mortality with warmer winters prove to be significant. Alternatively, the burden from heat waves could be greater than predicted if availability of cooled environments should decrease for any reason. It should be noted that with current air conditioning technology, creating cooled environments will have high economic and environmental costs, as air conditioners require significant consumption of energy that, in turn, results in more global warming. The true burden of temperature extremes will also be affected by future climate variability. Sustained warmth will tend to acclimate a given population to heat stress and lessen cold-induced cardiovascular stress, whereas more variable and intense temperatures will increase physiologic stress and associated mortality.

Extreme Events

Extreme weather events — severe storms, floods, and hurricanes — have well-documented short- and long-term effects on human health (Noji, 1997). Extensive precipitation producing floods, avalanches, or mudslides, and intense wind from hurricanes can cause immediate injury and death. Wind, flooding, or drought can also produce longer lasting and further reaching impacts on housing, food production, drinking water, and social infrastructure, which can result in infectious diseases and economic disruption. For the United States, the health impacts of extreme weather events have been more moderate than for most other parts of the world. Trends in direct mortality from floods, hurricanes, and severe storms have been sharply downward in the twentieth century, probably due to early warning, evacuations, and improved housing construction standards (Noji, 1997). Most deaths related to recent storms have been the result of either drownings in motor vehicles or accidental electrocutions.

Populations at risk from extreme weather events include those living in coastal and other vulnerable zones (e.g., flood zones). No published studies have modeled health consequences of extreme events related to climate change. Studies and surveillance following the severe flooding of North Carolina resulting from Hurricane Floyd in September 1999 will give greater insight into this country's vulnerability to extreme events.

Whether climate change will increase the frequency of extreme events in the United States is quite uncertain. Several authors have suggested an increase in the intensity of Atlantic hurricanes. Such an increase would be difficult to detect, however, because the changes in hurricanes from year-to-year are far greater than the expected increase in intensity due to increased GHGs (Wigley, 1999). While midlatitude storms are capable of affecting large parts of the United States, it is not yet possible to make useful predictions of their frequency or intensity in a setting of global climate change (Wigley, 1999). On the other hand, the observation of a trend toward increasing intensity of rainfall during the twentieth century (Karl et al., 1995) is consistent with predictions of a more active hydrologic cycle in a setting of increased GHGs. While specific regional impacts are not clear, flooding could become more common and extreme (Frederick and Gleick, 1999).

B. Indirect Health Effects

Respiratory Health

Global climate change may affect human health by changing levels of air pollutants and pollens. Climate conditions interact with air pollutants in a variety of ways. For example, air inversions in stagnant high pressure systems are associated with the highest levels of particulates, ozone, nitrogen oxides (NO_X), and sulfur oxides (SO_X), and heat waves are usually marked by high humidity and elevated levels of these same air pollutants. Warmer weather may enhance dispersion of fungal spores and pollen, which may increase allergic reactions and asthma. At the same time, increased winds and precipitation generally reduce airborne pollutants, including pollens, through dispersion or adsorption to water droplets.

The ultimate impact of climate on pollen-induced disease is difficult to predict, but will depend in part on whether local allergenic species increase or decline in response to climate changes. Since the start of the twentieth century, the length of the growing season has increased in much of the world, and further increases are likely with continued warming. A longer growing season would lead to greater cumulative exposures to pollens from weeds and grasses that tend to pollinate until the first annual frost. Longer-term changes in climate may lead to altered plant distribution and increases or declines in the numbers of allergen producing species (Emberlin, 1994). Additional factors, including ultraviolet radiation and air pollutant concentration, may change levels of pollen produced by plants or alter the allergenicity of pollen grains (e.g., Behrendt et al., 1997).

A substantial body of literature documents the health impacts of outdoor air pollutants (Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society, 1996a and b). For the United States, impacts of climate change on tropospheric (i.e., ground-level) ozone (commonly referred to as "smog") are both more certain and likely to be more important than impacts on other air pollutants given the importance of temperature in the formation of ozone (Walcek and Yuan, 1997). In addition, greater health significance is imparted by the fact that ozone is the criteria air pollutant to which the highest numbers of U.S. residents are currently exposed at levels above EPA standards (U.S. EPA, 1996b). It should be noted that despite a relatively direct impact of temperature on ozone levels, concurrent changes in wind, precipitation, and cloud cover may moderate the effect of temperature.

Models have estimated an increase in ground-level ozone for eight U.S. cities of around 2 to 4 percent if temperatures increase 2ºC and stratospheric (i.e., atmospheric) ozone depletion leads to increased ultraviolet radiation hitting the lower atmosphere (Grey et al., 1987). Thus, to the extent that higher ambient temperatures lead to a marginal increase in ground-level ozone concentration, a large proportion of the population would be at greater risk. Most affected would be those with underlying respiratory diseases, including asthma. People living in an area susceptible to high ozone levels, such as southern California or the northeastern and Mid-Atlantic states, would also be most affected. Although the literature on ozone effects in asthmatics is not wholly consistent, substantial data link higher ambient ozone concentrations to asthma exacerbation. Members of the general population experience mild lung inflammation due to high ozone levels; whether this inflammation leads to permanent lung damage is unclear. Thus, high temperatures may affect health through mechanisms besides heat alone as susceptibility to increased ozone concentrations will also affect the morbidity and mortality associated with a heat wave.

Aside from ozone, no published studies to date have modeled the effects of climate change on air pollution concentrations or the health impacts in the United States due to climate change effects on air pollutants. Lack of knowledge regarding climate impacts on other pollutants makes a comprehensive assessment of these impacts on human respiratory health highly uncertain.

Lastly, an important question is whether ambient temperatures or other climate factors alter the toxicity of air pollutants. As an example, might a given concentration of particulates cause more serious or more frequent adverse health effects at higher temperatures? There is some evidence of an impact of warmer temperatures on the effect of particulates on asthma exacerbation (de Diego et al., 1999) and on the effect of sulfur dioxides on overall mortality (Katsouyanni et al., 1993). On the other hand, using data from Philadelphia, Samet et al. (1998) did not find that weather altered the impact of exposure to particulates or sulfur dioxides on health. Unfortunately, most studies have aimed to prove independent effects of either weather or air pollution on respiratory health. The authors have analyzed data in such a way as to control for the effects of weather on respiratory health when studying air pollution, and vice versa, but not to be able to explicitly report on possible interactive effects. The answer to this question must therefore await further analysis of the interaction between air quality and climate factors in the study of respiratory health.

Climate Change and Sea-level Rise

Rising seas accelerated by global warming may adversely affect human health. Sea level is predicted to rise 0.2 to 0.9 meters by 2100 (Wigley, 1999). This rise in sea level will be experienced both as a gradual shift in the shoreline and as increasingly severe storm surges and damage from coastal storms (Neumann et al., 2000). These changes will threaten low-lying regions of the coastal United States to varying degrees. Because different regions of the United States are already rising or falling because of movement of the earth's crust, the actual relative change in sea level will vary in these different regions. For example, the Chesapeake Bay area, which is subsiding, is predicted to experience twice the average amount of sea-level rise, while the West Coast, which is rising, will experience a smaller than average sea-level rise (Neumann et al., 2000).

Sea-level rise may affect human health through saltwater intrusion into freshwater drinking supplies, damage to estuarine ecosystems that are essential for filtering wastes and/or providing breeding grounds for marine animals, and displacement of coastal communities. Higher sea levels may also lead to greater storm surges and destructive impacts of coastal storms (Neumann et al., 2000).

While sea-level rise may affect health via a wide variety of mechanisms, health impacts of sea-level rise in the United States may well be related to economic consequences. It is likely that the United States will have the economic resources necessary to protect critical coastal sanitary and drinking water infrastructure. Damage to critical coastal ecosystems, such as wetlands and coral reefs, and erosion of beaches, will be more difficult to avoid. Estimates for the costs of protecting coastal property have ranged from $20 billion to $150 billion (Neumann et al., 2000). These costs, however, do not fully account for loss of tourism revenue, loss of income from degraded fishing or shellfishing resources, loss of wetlands, or investments in drinking water and sanitary infrastructure. Communities in areas experiencing more severe sea-level rise, such as the Gulf Coast, Mid-Atlantic, and Chesapeake Bay, would also be affected more than those in areas where sea-level rise is not predicted to be as great. Potential community impacts such as decreases in income and unemployment are well-associated with poorer health status (Syme and Balfour, 1998; Sorlie et al., 1995). These indirect impacts have the potential to be greater than any primary impacts of sea-level rise on human health in this country.

Climate Impacts on Food Supplies

Climate changes associated with increased GHGs will alter agricultural productivity. Decreases in production may be related to alterations in rainfall patterns and decreased soil moisture, while increases have been predicted for certain crops because of increases in carbon dioxide and longer growing seasons (Adams et al., 1999). Significant decreases in agricultural productivity would threaten health should higher local food costs or unavailability make adequate nutritional intake difficult for any segment of the population. In the United States, there will be some variability in productivity among the different regions but overall little change or possibly increased production potential is anticipated in scenarios up to doubled carbon dioxide concentrations (Adams et al., 1999). The combined protection of a large land area in a temperate climate zone, well-developed transportation infrastructure, a strong economic and technological base, and access to international trade should minimize any impact of potential regional changes in food production on nutrition for the United States (Adams et al., 1999).

In addition to concerns about food quantity, climate change has raised concerns about bacterial contamination of food (Bentham and Langford, 1995). Food-borne infections generally are more common in the warm summer months, probably due in part to the fact that summertime is when most outdoor eating events take place in the United States, with associated storage of food outside of refrigerators. Higher ambient temperatures are likely to increase risk of bacterial growth sufficient to cause human infection. Contamination is not simply a concern for individual outdoor events, however. The growth of a highly centralized food processing and distributing industry over the past two decades in the United States has increased the importance of factors that can lead to the contamination of foodstuffs. Once again, contamination of food is a problem with multiple causal determinants, of which climate is only one.

No published studies projecting changes in food-borne illness under climate change scenarios have yet been published.

Vector-borne Diseases

Because insects and other invertebrates are cold-blooded and heavily dependent on the environment, climate plays a major role in their behavior, development, and reproduction. In addition, pathogen development is regulated by temperature. Thus, human diseases that are spread by these invertebrates may also be more affected by climate change than some other diseases. Vector-borne diseases result from transmission of infectious agents by arthropod vectors as they feed on human blood. Some vector-borne diseases such as malaria and dengue fever, termed anthroponoses, may be uniquely human infections in which an arthropod is able to transmit the microbe to another human only after first acquiring it from a human. Alternatively, many other vector-borne diseases of humans, termed zoonoses, involve infectious agents that normally are found primarily in animals, with occasional and accidental transmission to people. The animals act as reservoirs for the disease, serving as hosts for the reproduction of disease agents in between human outbreaks. Should climate change improve longevity, increase reproduction, enhance biting, or increase the ranges of these vectors, an increase in the number of people infected could result. Likewise, similar effects on the vertebrate animals that serve as reservoirs for agents associated with hantaviral diseases (infectious viral pulmonary diseases), leptospirosis (a bacteria disease characterized by jaundice and fever), rabies, or vector-borne diseases could also result in greater human risk.

The complex and multiple impacts of climate on the various factors that determine transmission of vector-borne diseases, however, make it extremely difficult to generalize about the mechanisms, much less predict in what direction changes may take place. Moreover, predicting climate impacts for zoonoses generally is more difficult than predictions for anthroponoses because of the involvement of these animal reservoirs in their transmission dynamics. Forecasts must be based on extrapolations derived from existing distributions, contemporary environmental tolerances, and current transmission frequencies. The fact that other important variables also are likely to change under various climate-change scenarios further complicates prediction.

The principal vector-borne diseases currently afflicting people living in the United States are transmitted either by mosquitoes (e.g., St. Louis encephalitis, equine encephalitis, and La Crosse encephalitis — all viral diseases associated with inflammation of the brain), ticks (e.g., Lyme disease, Rocky Mountain spotted fever, ehrlichiosis — a bacterial disease characterized by fever and fatigue), or fleas (plague). Studies have shown that aspects of these vectors' life cycles, survival, and behavior that are important to pathogen development or transmission are affected by climate variables, such as higher temperature, altered precipitation, or changes in wind and solar radiation (Reiter, 1988). Generally, it appears that mosquitoes are more sensitive than ticks and fleas to such climate variability (Kettle, 1995). Thus, previous assessments have suggested that climate change may result in certain mosquito-borne diseases such as St. Louis encephalitis becoming more frequent in areas where they currently are rare (Reeves et al., 1994). Similarly, it has been proposed that western equine encephalitis may appear after future heavy precipitation events (Nasci and Moore, 1998). Other studies have characterized how wind trajectories and flooding can either increase or decrease vector densities or distribution (e.g., Patz and Lindsay, 1999). Interestingly, the outbreak in New York City during the late summer of 1999 of West Nile-like viral encephalitis, which is similar to St. Louis encephalitis, was attributable to the summer drought conditions. Specifically, while it is believed that the West Nile virus was recently introduced into the United States (Lanciotti et al., 1999), the likely vectors in that setting (certain *Culex* or *Aedes* mosquitoes) were common to the New York area (Anderson et al., 1999). Because some *Culex* larvae develop primarily in stagnant water, summer drought conditions may have allowed water in sewers and unused swimming pools to stagnate, producing ideal conditions for this mosquito, thus increasing transmission of West Nile virus (Wilgoren, 1999).

Most concern over climate change effects on infectious diseases has focused on the unfamiliar "foreign" mosquito-borne diseases, such as malaria (caused by *Plasmodium* parasites), dengue fever, and, more recently, West Nile virus along the northeastern coast. Dengue fever and malaria may occasionally be introduced into the United States, but neither is regularly transmitted there. The vast majority of cases of dengue and malaria among U.S. residents are acquired by tourists visiting countries where these diseases are indigenous, and generally do not present a threat to people living within the United States. West Nile virus, however, appears to have become established after overwintering and reappearing during the summer and fall of 2000 throughout an increasingly large area of the northeastern United States. While climate change is predicted to gradually increase the regions of the world where conditions are suitable to the mosquito vectors, there are already many such suitable regions where these mosquitoes are present but transmission does not occur. The reasons for this vary depending on conditions, but either the mosquito species that are efficient vectors are not abundant, they rarely are in contact with people, or the infectious agent is not often present in people. In regions where such diseases are already endemic, these conditions exist. In the United States, there is reduced mosquito abundance, limited contact with people, and low infection levels such that mosquitoes' mere presence is inadequate to allow persistent transmission. Even the occasional introduction of an infected person is inadequate to provoke a local epidemic. Thus, even if climatic conditions were to change such that efficient vectors became more abundant or widespread in the United States, other conditions needed for transmission of these infectious agents would be required for the disease to appear or become important.

For example, in climatically similar border regions of southern Texas and northern Mexico, locally acquired dengue occasionally occurs in Texas whereas transmission is usually much more intense in adjacent areas of Mexico. Despite suitable environmental conditions in Texas for *Aedes aegypti,* the mosquito vector, mosquito control and other protective efforts have kept dengue to extremely low levels there. Similarly, locally-acquired malaria is very rare in the United States because the *Anopheles* mosquito-vectors that are present have been kept to low numbers. Furthermore, the *Plasmodium* parasite is rarely identified within mosquitoes, and then only when an infected person unintentionally introduces the parasite.

Because of the presence of mosquitoes that are able to act as disease vectors, vector-control efforts in the United States and public health surveillance will continue to be an important deterrent to these diseases, regardless of changes in climate. As long as these control measures remain intact, climate change is not likely to significantly increase the domestic risk from malaria and dengue. Reduction of mosquito abundance (e.g., removing breeding sites, spraying, etc.), limitation of feeding on people (e.g., housing conditions, repellants, etc.), and the regional absence of infected people (i.e., travelers are vaccinated or given preventative medication) all contribute to reduced risk of introduction. The greater risk for these diseases among U.S. residents will remain related to travel to areas where *Anopheles* and *Aedes aegypti* mosquitoes are abundant, and disease transmission already occurs.

Studies of tick-borne zoonotic diseases such as Lyme disease (see Box 3) or human ehrlichiosis have demonstrated that incidence and distribution are strongly linked to environmental variables, but the role that climate change may play in the future epidemiology of transmission is not well understood. Lyme disease may be linked to differences in tick abundance associated with precipitation and elevation (Amerasinghe et al., 1992), and is associated with habitat characteristics in a complex manner (Wilson, 1998). However, the role that climate change may play in altering the range and local abundance of Lyme

Box 3

Lyme Disease

Lyme disease is a tick vector-borne disease that is widespread throughout much of the northeastern United States, parts of the northern Midwest (especially Wisconsin and Minnesota), and California. In most areas infested with the vector tick (*Ixodes scapularis*), the Lyme disease-causing bacteria (*Borrelia burgdorferi*) are present and, thus, the potential for human infection exists. However, transmission depends on many factors, most importantly the abundance of ticks, the percentage of ticks infected, their survival, the activities of people in relation to habitats of ticks, and people's knowledge and awareness concerning tick bites and Lyme disease prevention. The range of the vector tick and of Lyme disease cases has been expanding over the past few decades, and the current distributions of the deer tick and of Lyme disease in the United States span a wide range of climatic conditions. While the factors that currently limit the distribution of this vector tick remain poorly understood, research suggests that microclimate, abundant hosts, and suitable vegetation and soil habitat are important.

One concern is that since present climate patterns influence the distribution of deer ticks, climate change might permit wider or more rapid expansion of this tick's range. Most climate change scenarios indicate that some regions of the United States may become warmer and moister, leading to speculation that the range of *Ixodes scapularis* might expand. Curiously, seemingly appropriate elements exist in many areas of the United States where this tick has not yet become established or widespread. Thus, even where a suitable microclimate is present, large vertebrates such as white-tailed deer are abundant (permitting adult female ticks to feed and reproduce), and diverse small mammals are frequently encountered (these species serve as hosts to immature ticks), the tick vector may not be present. While it may be just a matter of time, at present there is no adequate explanation for this observation. At the same time, this tick currently tolerates cold and generally moist conditions in Minnesota, Maine, and parts of southern Canada, suggesting that low winter temperatures are not currently limiting. In fact, tick abundance does not correlate with increasing temperatures. Lastly, while increased precipitation might permit longer survival of unfed ticks, which are highly susceptible to desiccation, deer ticks are currently found in some regions with average precipitation that is less than that forecasted under climate change scenarios.

Thus, while some have speculated that climate change might increase the rate of spread of this disease or shift the areas that are susceptible, various factors other than climate appear to be primarily responsible for risk of this vector-borne disease.

disease vector ticks (principally *Ixodes scapularis*) is speculative. The same holds for other tick species that serve as vectors of certain Ehrlichia parasites that cause febrile disease in humans (Vail and Smith, 1998; Lindsay, et al., 1999). Again, climate assessments generally have interpreted these observations cautiously, suggesting that climate change may alter the distribution or local incidence of human ehrlichiosis if tick abundance, survival, or feeding behavior were to be modified. Rocky Mountain spotted fever, caused by a bacterium that is transmitted by particular species of *Dermacentor* ticks, is yet another tick-borne disease that might be altered if changes in tick abundance result. Nevertheless, studies of this possibility are not able to go beyond suggestion and speculation.

Of flea-borne zoonotic diseases, plague (the "Black Death" of history) is still a concern in regions of the United States where flea-infested mammals are abundant (Campbell and Dennis, 1998). During the past few decades, most human cases have occurred in northern New Mexico, northern Arizona, and southern Colorado, in addition to other cases in California, southern Oregon, and far western Nevada (Gage, 1998). Because vertebrate reservoir abundance and survival is a major determinant of flea movement to humans and other hosts, the role of climate in the spread of plague beyond its normal reservoir hosts is unclear. While climate change may alter the abundance and interactions of host and vector, little concrete evidence is available to indicate that human health risks will be significantly changed.

Overall, most assessments examining studies of climate impacts on vector-borne diseases currently found in the United States have not been able to make strong, definitive statements about how projected climate change may impact health (e.g., Patz et al., 2000). Not only are the observations few and the links sometimes weak, but just as other intervening variables are typically not considered, neither is pathogen evolution or adaptation to new and existing environments (e.g., Reiter, 1996).

Water-borne Diseases

Several mechanisms have been proposed to link climate and climate variability to water-borne infectious diseases, generally in association with specific infectious agents. Climate factors (ambient temperature and rainfall) are among various factors affecting survival and replication of bacteria and viruses in the general environment. Warmer temperatures tend to improve survival of bacteria and may facilitate the transmission of certain water-borne illnesses, while many viruses persist for longer times in colder temperatures. A growing body of evidence shows that the cholera bacterium, *Vibrio cholerae,* survives between outbreaks of human disease in a dormant form attached to small zooplankton in coastal waters (Colwell, 1996). Cholera outbreaks in Bangladesh have been associated with water surface temperatures (Colwell, 1996). Likewise, it has been hypothesized that the anomalous warm sea temperatures associated with the El Niño phenomenon contributed to the simultaneous outbreak of cholera in South America in 1991-1992, the first such outbreak in the twentieth century.

Cholera is not a major health threat in the United States because virtually all surface waters consumed as drinking water are chlorinated, which effectively kills the cholera bacteria. Nevertheless, cholera outbreaks occurred in the United States throughout the nineteenth century, and the *Vibrio cholerae* bacterium is still present in U.S. coastal waters, particularly the Gulf of Mexico (Weber et al., 1994). The few sporadic cases in the United States occur generally as a result of ingestion of the bacteria by consuming contaminated, uncooked seafood (Weber et al., 1994). Because sanitary facilities and water treatment are widespread, sporadic cholera outbreaks in the United States have not resulted in widespread epidemics like those in South America or southern Asia (see Box 4). While warming coastal water temperatures and other climate-associated factors may increase the numbers of viable cholera bacteria in the water and in seafood, large epidemics in the United States are highly unlikely so long as the water and sewage treatment infrastructure remains functional.

Another water-borne disease, cryptosporidiosis, an intestinal disease caused by species of *Cryptosporidium* protozoa, is likely to be responsive to high rainfall events. *Cryptosporidium* oocysts are resistant to chlorination and are very small, making them more difficult to kill or filter out than most bacteria in the water supply. *Cryptosporidium* species are also widespread in livestock feces on farms. Thus, large amounts of rainfall may bring *Cryptosporidia* into surface waters through runoff. Large amounts of rainfall also place greater stress on sewage treatment plants, particularly those that do not separate sanitary sewers from storm drainage. Under these stress conditions, sewage treatment plants may release

Box 4

International Health Impacts

Because most health impacts that are associated with climate currently exact a greater toll on underdeveloped countries than on developed countries, it is anticipated that climate change will disproportionately impact these poor nations relative to more developed countries. Today, for example, 95 percent of the mortality related to extreme weather events around the world is suffered by the poorest 66 percent of the world's nations (Anderson, 1991). The difficulty poorer nations have in creating the necessary infrastructure to address extreme events and natural disasters such as floods and hurricanes is likely to render them even more vulnerable should climate change increase the frequency or severity of such extreme events.

In addition to health effects from extreme events, population displacement from sea-level rise, disruption of food supplies leading to malnutrition, and increased incidence of vector- or water-borne diseases also are more likely to be exacerbated in the developing world as a result of climate change. Projections of food production under climate change scenarios indicate significant regional variability (Watson et al., 1996). Unfortunately, many regions that currently have serious malnutrition and starvation, such as sub-Saharan Africa and India, are projected to experience even less favorable conditions for agriculture under climate change scenarios (Parry and Rosenzweig, 1993). Most underdeveloped countries have inadequate facilities for water treatment and storage, making shifts in precipitation in either direction likely to disproportionately increase water-borne and water-associated diseases. Areas that currently experience vector-borne diseases, especially those where cool seasonal temperatures limit current transmission, are more likely to experience climate-related increases in transmission. These impacts will be greater in those underdeveloped countries characterized by poor housing quality and social disorganization that prohibits effective vector control programs. Overall, the burden of climate change-related impacts on health is likely to be greatest in countries that currently are least capable of responding to such changes.

greater amounts of *Cryptosporidia* into surface waters. Ultimately, large outbreaks of cryptosporidiosis, such as the one that occurred in Milwaukee in 1993, are due to failures of drinking water treatment, particularly filtration.

Because of population pressures and growing opportunities for cross contamination of sewage and potable water systems, improved survival of organisms could lead to higher rates of disease, particularly among populations drinking unfiltered spring or groundwater. To date, however, no systematic studies have been done to assess risks of water-borne disease increases from climate change. As appears to be the case with recent cholera and cryptosporidiosis cases in the United States, climate factors may increase concentrations of the organism in source waters; the ultimate health impact depends on the success of water treatment technology to remove or inactivate the organisms.

IV. Strengths and Limitations of the Current State of Knowledge

A. Issues Related to the Quality of the Scientific Literature

The reliability of analyses of health impacts of climate change depends on the quality of data sources. In general, the assessment of health impacts of climate change has used the following types of information:

- comparisons of disease patterns among different places with different average climates;
- contrasts of disease patterns in one location in association with short-term climate variability;
- analysis of long-term historical trends in climate and disease;
- experimental or perturbation studies of biophysical mechanisms;
- statistical extrapolations based on past patterns and trends; and
- model simulations based on partial knowledge of interactions and processes.

Confidence in each of the inferences regarding health and climate change depends upon the complexity of the health impact in question and the type of information used to make the inference. There should be more confidence in projected health impacts of climate change when:

- the effect is direct and does not involve multiple steps;
- the mechanism of climate impact is well understood;
- the relation between change in the climate factor and change in the health outcome is well-characterized (analogous to "dose-response");
- there is a substantial body of literature documenting the relation between climate and health outcome in a variety of geographic settings;
- there are few non-climate determinants of the health outcome; or

- non-climate determinants of the health outcome are likely to remain constant over the time interval considered. This situation is most likely in health outcomes related to short-term climate variability.

Rarely do studies of projected health impacts from climate change meet these criteria. How these factors influence current knowledge and confidence in forecasted impacts is briefly summarized below.

The greatest confidence can be given to forecasts of climate change impacts on health when the pathways of effect are rapid, simple, and direct. This is most applicable to health impacts of unusual weather events involving extreme temperatures and severe storms. If climate change projections that indicate more extreme weather events are correct, then an increased incidence of heat- and storm-related deaths is likely to result. Even though the weather forecasting capacity and civil preparedness in the United States are already well-organized, further improvements in these defenses would lessen the health impact of an increase in heat or storm events. Thus, both current knowledge and the ability to use this knowledge are greatest in the area of impacts from extreme events.

Other health impacts result from indirect pathways with many variables in the causal chain. In general, understanding and predictive capacity decrease rapidly as more and more intermediate variables are added. This is the situation with many infectious diseases — not only do the impacts of climate variability on intermediate factors differ, but also the factors themselves interact in various kinds of feedback. For this reason, the ability to forecast long-term patterns of many diseases with more complex ecosystem links is very rudimentary.

B. Lack of Baseline Data on Human Disease Incidence

For most health impacts, the baseline data needed to carefully analyze possible health impacts are inadequate, thus severely limiting understanding of these impacts. Empirical research on changes in disease requires long-term surveillance records to be able to compare similar long-term data on climate variability. Lacking this information for most diseases, the process of inference and forecasting must rely on other, more speculative approaches. Even where comparable data for a few decades exist, it is unclear whether the short-term fluctuations and extremes they contain can be used as a surrogate for longer-term climate trends (see Box 2). Nevertheless, such surveillance data are critical for many analyses and will serve as the basis of any “early warning” efforts based on short-term climate variability.

C. Few Studies of Climate and Disease Interactions

Overall, knowledge of potential health impacts is based on a very small body of appropriate research. A review of the literature suggests that, despite many published reports that address the possible impact of climate change on health, only a small minority present rigorous scientific research involving data collection, statistical analysis, or simulation modeling. The majority of published reports, including those in major scientific journals, represent summaries, reviews, or efforts to speculate on possible impacts. Except for heat-related mortality and extreme event impacts, the extent of solid scientific research on which most discussions of health impacts rest is less than what most scientists would require to have confidence in the conclusions.

D. Future Climate Change and Variability

As with all sectors, assessing the potential health impacts of climate change first requires understanding how climate change will manifest itself over the time period to be assessed. GCM models have provided fairly consistent estimates of temperature changes related to increased GHG concentrations. They have been less consistent in their predictions of precipitation trends, and much uncertainty remains in predictions of how climate variability, as well as the frequency of extreme events, will be affected by increasing concentrations of GHGs (Wigley, 1999). Studies to date have often dealt with this problem by superimposing current variability on projected increases in average temperature. In addition, the current low resolution of GCMs makes it very difficult to predict climate change on a smaller, regional to local scale. Accurate assessment of future health impacts will require an enhanced ability to predict climate change at a finer geographic resolution and at the full range of time scales needed to assess climate variability.

E. Validity of Comparing Different Regions to Approximate Future Climate Changes

Results of studies from specific geographic areas may not be valid in predicting changes for other parts of the world. Thus, simulation models that project increased risk of malaria epidemics in areas where vector mosquitoes might expand may be more appropriate in Africa, where transmission is already widespread and prevention difficult, than in the United States, where many means of combating transmission exist. Similarly, studies suggesting the appearance of similar diseases in regions where future climate may become like that of the present climate in another part of the world ignore many other important ecological, social, behavioral, and economic determinants. In general, extreme caution must be exercised in interpreting studies that use space as a substitute for time. Enormous changes in the distribution and incidence of many diseases have occurred in the absence of major changes in climate. Within the past decade or two, dozens of emerging and re-emerging diseases have appeared and reappeared throughout the world, primarily as the result of increased air travel, antibiotic drug resistance, civil strife, urbanization, crowding, and deforestation. These and other non-climate factors, which may be difficult to predict, are likely to remain major determinants of changes in the spatial pattern of diseases in the future.

F. Future Steps

While it is relatively easy to point out insufficiencies and uncertainties in current assessments, it is more difficult to suggest the steps that might be taken in the face of such uncertainty to protect public health most fully and efficiently. It should be remembered that uncertainty regarding adverse health outcomes is not the same as the certainty of no adverse outcomes. Given the potential scope and irreversibility of ecosystem changes and consequent effects on human health and society, traditional public health values would urge prudent action to prevent such changes. The great challenge is to select actions that provide benefits over a wide range of future climate change possibilities, and that minimize economic costs that would bring their own negative impacts on public health. A summary of the health impacts discussed in this paper (including information on which populations are most affected and the non-climate determinants of each impact) and potential adaptation options appears in Table 4.

Table 4

Characteristics of Potential Health Impacts of Climate Change

Impact	Populations most affected	Potential additional U.S. public health burden due to climate change	Complexity of system	Other, non-climate determinants	Adaptation measures
Heat stress	Elderly, those with respiratory disease, infants	Low	Low	Acclimation, architecture, air conditioning	Architecture, air conditioning
Extreme weather events	Coastal, low-lying land, low SES[1]	Uncertain	Low	Architecture, early warning, engineering (levies, sea walls)	Architecture, early warning, engineering (levies, sea walls)
Sea-level rise	Coastal, low SES	Low	Moderate	Coastal pollution, storms, development, and land use planning	Sea walls, abandonment
Respiratory disease due to air pollution	Elderly, those with respiratory disease	Low to Moderate; potential improvement due to GHG mitigation	Moderate	Cigarette use, respiratory infections, air regulations, industrial activity, automobile use, aeroallergens, access to care	Technological advances in efficiency, pollution controls, regulations, staying indoors
Food supply/ Malnutrition	Low SES, elderly, children	Very Low	Moderate	Food distribution systems, economic/trade issues, population growth, bio-technology	Food distribution systems, technological advances, enhanced climate forecasting
Malaria	Infants, young adults	Low	High	Travel, vector control measures, public health infrastructure, drugs, drug resistance	Public health surveillance, R&D for drugs, vaccine, and safe pesticides
Dengue	Children, especially with previous dengue infection	Low	High	Travel, vector control measures, public health infrastructure	Public health surveillance, R&D for drugs, vaccine, and safe pesticides
Lyme disease	Suburban population	Uncertain	High	Deer and mouse populations, land use	Public education, vaccine, clinical care
Hantavirus	Young adults, rural population	Uncertain	High	Land use, vegetation, mouse population, housing quality	Public education, public health surveillance
Cholera	Coastal populations	Low	High	Waste and drinking water treatment, access to care	Maintenance of sanitary infrastructure, possible vaccine, clinical care, avoidance of coastal food sources
Cryptosporidiosis	Immunosuppressed individuals	Low to Moderate	Moderate	Waste and drinking water treatment, watershed preservation	Increased water filtration
Other waterborne infections	Infants, elderly	Low to Moderate	Moderate	Waste and drinking water treatment, watershed preservation	More widespread water treatment, including groundwater sources
International conflict	General population	Highly uncertain, potentially high	High	Sociopolitical change, resource conflicts	Improved international mediation of resource conflicts

[1]SES: socio-economic status.

V. Gaps in Current Assessments

A. Consideration of Cross-Sectoral Political and Economic Impacts

To date, most human health impact assessments have assembled published investigations and analyses from a wide variety of disciplines, and catalogued the evidence for changes in the rates of specific diseases and health outcomes. Such a "synthesis" is a difficult undertaking, not only because of the unevenness in quality and type of investigations, but also because overall impacts on human health will undoubtedly be more than the simple sum of projections of individual diseases. Previous sections highlighted the important interrelations between socioeconomic conditions and human health. The disruption of natural systems predicted under global climate change is likely to have economic impacts around the world, and, to some extent, in the United States as well. Climate change assessments have predicted changes on a sectoral basis, separating possible impacts on coastal zones, forests, agriculture, water resources, etc. Adaptive and other responses to climate change in these other sectors will most certainly require diversion of societal resources. These economic changes due to impacts on other sectors have not been analyzed in most health impact assessments in a comprehensive fashion, due in part to the significant increase in complexity such an inclusion would entail, and in part to the fact that the relations between economic determinants and human health have not been adequately characterized. Thus, health impact predictions have been developed under the assumption that most non-climate health determinants will not change significantly. And yet these very determinants may not only be more powerful than climate change, they may also be significantly altered as a result of climate change. While this gap is not easily filled at present, it is one that needs to be considered as a source of considerable potential adverse impact on human health; the whole may indeed be greater than the sum of the analyzable parts.

B. Psychological Effects

Consideration of the psychological effects of global climate change has been absent or insubstantial in most reports to date. There are several reasons for this, including the difficulty in associating mental heath effects with environmental changes, and the unprecedented nature of climate change. Nonetheless, studies suggest that adverse mental health consequences may result if climate change results in either clearly perceivable ecological disruption, frequent severe storms, or severe disease outbreaks. Baum and Fleming (1993) have suggested that human-caused stressors contribute more than naturally occurring stressors to chronic stress and other persistent health problems. Specific stressors related to acute traumatic events have included suffering intentional injury and/or harm, causing harm to another, and learning of exposure to a factor that may cause harm over a long period of time (Green, 1993). Whether these stressors, identified from observations of acute trauma, will also be important in the setting of chronic environmental disruption remains to be determined.

C. International and Intranational Conflict and War

While international conflict has been listed as a possible consequence of climate change with health impacts, it has generally attracted much less attention than human diseases. For the United States, however, international political consequences may ultimately affect health more than changes in local disease rates. A study commissioned by the Carnegie Foundation noted that stressors related to environmental deterioration interact with historical tensions and other political conflicts (Kennedy et al., 1998). The report concluded that climate impacts on agricultural production, water resources, human diseases, and inundation of coastal zones may exacerbate existing instability and tension in areas such as the Middle East, southern Africa, and southern Asia. While perhaps speculative in the case of climate change, the concept that international health crises constitute a U.S. security threat has recently emerged in connection with the AIDS epidemic (Gellman, 2000).

VI. Research Needs in Climate Change and Health

Major research efforts are needed to understand and eventually protect against possible health impacts of climate change. However, the complexity of these problems, involving many different diseases and health consequences that vary among social groups and regions of the United States, is daunting. Most changes in disease patterns or health determinants will involve diverse biological and physical systems spread over a large area, and these changes will play out over a relatively long period of time. Given current analytic tools and methods, this level of complexity introduces so much uncertainty into any prediction of future health that the usefulness of such a forecast is very limited. First and foremost, the development of a useful research program will require more robust, systematic, and long-term disease surveillance. Many current studies and modeling efforts are limited by a regrettable lack of such surveillance data. With such data, the further development of new integrative methods for studying climate-health interactions will be facilitated. This section addresses some of these needs and recommends where opportunities should be exploited.

A. Enhanced, Systematic, Long-Term Monitoring and Surveillance

As has been recognized by many recent panels addressing the problem of emerging diseases, disease surveillance in the United States, as well as surveillance assistance to other countries, is woefully inadequate. Without systematically gathered epidemiological records, there is not enough basic information to track and retrospectively analyze changes in disease patterns. Not only does disease information differ among cities and states, but also the variable extent of voluntary reporting makes some surveillance data difficult to interpret. These data are critical to studies aimed at understanding disease trends, analyzing changes associated with the environment, and eventually anticipating future outbreaks and situations of high risk. Historically, such data have been vital to developing hypotheses of causal links, and may be the only way to test these predictions prospectively. In addition to the important role that surveillance plays in recognizing new and re-emerging diseases, high quality disease data are critical to studies of climate impacts on health.

B. Ecologically Based Research and Evaluation

The vast majority of health research in the United States today involves treating disease rather than preventing it in the first place. A new research emphasis is needed that focuses on identifying and understanding disease-specific environmental factors that can be used to prevent many cases of disease before they occur. Climate variables are only a few of many such environmental factors. Based on the limited understanding of individual ecological and physiologic mechanisms that underlie exposure and human response, focused experiments are needed to explore how multiple variables interact and what different impacts they have on health outcomes. Classical laboratory experiments aimed at demonstrating dose-response or transmission of infectious agents cannot fully replicate the diverse conditions that occur under natural climate variation. Unfortunately, the nature of the current research funding system has lead to an increasing focus on simple experiments that produce rapid results, at the expense of studies producing long-term prospective observations. In addition, new experiments that evaluate how changing environments may lead to rapid evolution will increase understanding of how adaptation may occur in the face of climate change during the twenty-first century.

C. Multidisciplinary Perspectives and New Analytic Techniques

As information needs change, not only must the design of observations be improved, but also new methods for gathering or analyzing data and interpreting patterns become important. The recognition that complex interactions among physical, biological, and socioeconomic variables determine disease risk argues that multidisciplinary studies of multiple variables are needed. The major determinants of health outcomes involve not only traditional disciplines such as climatology, immunology, or physiology, but also sociology, psychology, and economics, among others. In particular, methods for the analysis of interactions among qualitatively different kinds of variables are needed to address the complex processes that occur as climate change affects health. Simulation modeling and system dynamics of complex interactions that include socioeconomic and behavioral adaptation need additional development. Implied in this is an increasing need for scholars with a breadth of knowledge and integrative perspective who will be able to work with specialists. Academic programs will need to be developed to train scientists in developing methods of studying climate change and health issues.

D. Planning that Integrates Health Concerns into Economic Development

Ultimately, a new approach to planning for economic development is needed that incorporates knowledge gained from such novel multidisciplinary research initiatives. Indeed, development planners could work more closely with health and environment researchers to define the direction of development and the knowledge needs that will inform policy decisions about that development. In a complementary manner, health goals could be incorporated into the planning process rather than added on after plans have been completed. Such a restructuring and coordination of intentional environmental change, impacts assessment, and health and environment input will be facilitated by collaborative research among business management, public administration, and environmental health experts.

VII. Conclusions

1. The complexity of the pathways by which climate affects health makes it extremely difficult to predict exactly how, when, where, and to what extent global climate change will influence human well-being. Nonetheless, our understanding of the linkages between climate and health makes it reasonable to anticipate changes in the risks of illness and injury as a consequence of climate change. Some risks may decrease, such as wintertime mortality from cardiovascular disease. Other risks may increase, including those from heat stress, ozone air pollution, water-borne illnesses, and certain vector-borne diseases. In general, the United States should have sufficient resources to address increased health risks and limit the actual occurrence of climate-related illness and injury. It will require, however, advance planning and commitment of resources to achieve this protection.

2. Uncertainty regarding adverse health outcomes is not the same as the certainty of no adverse outcomes. Given the complexities of the various factors involved with disease persistence and transmission, society must also be prepared to "expect the unexpected." This may involve unpredicted sudden severe shifts in climate, the emergence of new diseases, or an unexpected synergy among various social, economic, and natural systems. The possibility of relatively sudden but unpredictable consequences raises the value of climate change mitigation for health concerns.

3. The linkage between warmer temperatures and increased heat stress is well-defined, and the relative certainty that summertime temperatures will increase in the near future makes worsened heat-related mortality the most certain of potential health impacts. The linkage between extreme weather events and injuries and illness is similarly well-defined, but there is less certainty regarding the frequency of extreme events in the near future. The ultimate effect of climate change on these health problems will depend on the balance between changes in local weather and emergency preparedness and other protective measures. Changes in climate are also predicted to affect air pollutant concentrations, with the association between warmer temperatures and increased ozone production being the strongest. Since changes in weather may either increase or decrease air pollutant concentrations, the ultimate impact of climate change on respiratory health is unclear.

4. Determining who in the population is most vulnerable to the health impacts of climate change depends strongly on the health impact being considered. The elderly, the very young, and those with underlying heart or lung disease will be most affected by heat stress and increased air pollutants. Vector-borne diseases tend to be more severe in the very young, but this varies by specific disease. Since many of the potential health impacts of climate change will not be realized for decades, today's children and future generations could be considered the population most affected by current decisions on climate change. In addition, health impacts of climate change are likely to be far more severe in developing countries where climate-sensitive diseases are currently major health problems, and where additional resources to protect the population's health are often not available.

5. Diseases with the greatest potential public health impact are typically multifactorial and among the most difficult to model and forecast. Modeling the complex pathways of vector-borne infectious diseases, for example, often requires information specific to the local region and species for greatest accuracy. Observations of infectious disease responses to climate variability suggest that climate can be an important factor in disease incidence, but applying these observations of short-term variability to longer-term climate changes increases the uncertainty of the prediction, and may not be appropriate. The complexity of these interactions, the variable time frames over which change may occur, and the multiple factors that are important all suggest a need for enhanced research efforts aimed at analysis of mechanisms and improved understanding.

6. Focus should be maintained not only on potential changes in disease pathways, but also on societal vulnerability to health impacts of climate change and what is needed to maintain the systems that decrease that vulnerability. These systems include water and utility infrastructure, housing and urban planning, and a strong U.S. economy in general. Integrating public health and climate change experts into land-use and utility infrastructure planning will help assure maximal protection of public health during this upcoming period of climate change.

7. In the United States, public health infrastructure has controlled most of the infectious disease risks that are felt to be most climate sensitive (e.g., dengue, malaria, cholera); climate change may increase the current very low chance that these diseases could re-establish themselves through ecosystem changes, changes in vector and disease agent survival, and possibly increased migration of infected individuals. It may also increase the frequency of sporadic disease outbreaks that currently occur extremely rarely. Maintenance and strengthening of public health systems, especially surveillance and vector control, will be critical to preventing significant outbreaks in the future. Public health systems also will be critical in implementing early warning systems and other interventions for heat-related mortality and air pollution exceedances. Since most of these health problems may be exacerbated by a multitude of factors unrelated to climate, such an investment in public health infrastructure is likely to have benefits with or without significant climate change.

Endnotes

1. The Established Market Economies are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Malta, Monaco, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States.

2. The Clean Air Act of 1970 identified carbon monoxide, lead, nitrogen oxides, ozone, particulates, and sulfur oxides as the six air pollutants most in need of standards, or "criteria."

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notes