# CHAPTER 15

# POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR HUMAN HEALTH IN THE UNITED STATES

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# PREFACE

Projections of the extent and direction of the potential health impacts of climate variability and change are extremely difficult to make because of the many confounding and poorly understood factors associated with potential health outcomes,population vulnerability, and adaptation.In fact,the relationship between weather and specific health outcomes is understood for a relatively small number of diseases, with few quantitative models available for analysis. The costs,benefits and availability of resources to address adaptation measures also require evaluation. Research aimed at filling the priority knowledge gaps identified in this assessment would allow for more quantitative assessments in the future.

# CHAPTER SUMMARY

Because human health is intricately bound to weather and the many complex natural systems it affects,it is possible that climate change as projected will have a measurable impact,both beneficial and adverse,on health outcomes associated with weather and/or climate. We identified and assessed five such categories of health outcomes:1) temperature-related morbidity and mortality;2) health effects of extreme weather events (i.e.,storms,tornadoes,hurricanes,and precipitation extremes);3) air pollution-related health effects;4) water- and food-borne diseases;and 5) insect-,tick-,and rodent-borne diseases.

Temperature-related Morbidity and Mortality
The more frequent heat waves projected to accompany climate change would pose a risk,particularly against the backdrop of an aging US population,as the elderly are most susceptible to dying from extreme heat.Beyond individual behavioral changes, adaptation measures include development of community-wide heat emergency plans,improved heat warning systems,and better heat-related illness management plans.Death rates are higher in winter than in summer and it is possible that milder winters could reduce deaths in winter months.However, the relationship between winter weather and mortality has been difficult to interpret.The net effect on winter mortality from climatic changes is uncertain and the overall balance between changes in summer and winter weather-related deaths is unknown.

Extreme weather events-related health effects
Health impacts from weather disasters range from acute trauma and drowning,to more medium- and long-term effects,such as conditions of unsafe water, and post traumatic stress disorder (PTSD). The health impacts of extreme weather events such as floods and storms hinge on the vulnerabilities of the natural environment and the local population,as well as on their capacity to recover.The location of development in high-risk areas increases a community's vulnerability to extreme weather events.Adverse health outcomes in the US are low compared with global figures partly because of the many federal,state,and local government agencies and non governmental organizations (NGOs) engaged in disaster planning,early warning,and response.

Air pollution-related health effects
Quantitative studies of the potential effects of climate change on air quality have primarily focused on the impact of increased temperature and ultraviolet radiation on ozone formation.In general, these few studies find that ozone concentrations increase as temperatures rise.The specific type of change (i.e.,local, regional,or global),the direction of change in a particular location (i.e.,positive or negative),and the magnitude of change in overall air quality (i.e., for all of the criteria air pollutants) that may be attributable to climate change,however, are not known.Additionally, climate change may alter the distribution and types of airborne allergens.

Emissions scenarios are central to assessing future air quality in addition to assessing the effect of altered weather on specific air pollutant formation and/or transport.Integrated air quality modeling studies will be necessary to assess more quantitatively the potential health impacts of air quality changes associated with global climate change.

Water- and food-borne diseases
Weather influences the transport of microbial agents,via rainfall runoff over contaminated sources.Temperature also influences the occurrence of bacterial agents,toxic algal blooms (red tides),and survival of viral pathogens that cause shellfish poisoning. Management of sewage and other wastes,and watershed protection are important to reducing health risks. Federal and state regulations protect much of the US population. Nonetheless,if climate variability increases,current

deficiencies in watershed protection and storm drainage systems will probably increase the risk of contamination events.

Insect-, tick-, and rodent-borne diseases
The ecology and transmission dynamics of insect- and rodent-borne infections are complex and unique for each disease.Many of these diseases exhibit a distinct seasonal pattern,suggestive of weather sensitivity. But demographic,sociological and ecological factors also play a critical role in determining disease transmission.The moderating effect of these other factors makes it unlikely that increasing temperatures alone will have a major impact on tropical diseases spreading into the US. There is greater uncertainty regarding more indigenous diseases that cycle through animals and can also infect humans.Further studies of transmission dynamics,and of pathogen, vector, and animal reservoir host ecology are required to determine whether these diseases will increase or decrease with climate change.

## Key Findings

- Multiple levels of uncertainty preclude any definitive statement on the direction of potential future change for each of the health outcomes assessed.
- Although our report mainly addresses adverse health outcomes,some positive health outcomes were identified,notably reduced cold-weather mortality, which has not been extensively examined.
- At present, much of the US population is protected against adverse health outcomes associated with weather and/or climate,although certain demographic and geographic populations are at increased risk.
- Vigilance in the maintenance and improvement of public health systems and their responsiveness to changing climate conditions and to identified vulnerable subpopulations should help to protect the US population from adverse health outcomes of projected climate change.

# POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR HUMAN HEALTH IN THE UNITED STATES

## INTRODUCTION

This chapter is based on a literature review and consultation with experts,interested researchers,and members of the public health community. Using,as an underlying set of assumptions, climate change projections developed for the national assessment, we analyzed the potential relationships between climate variability, climate change,and human health within a given framework of questions:

- What is the current status of the nation's health and what are current stresses on our health?
- How might climate variability and change affect the country's health and existing or predicted stresses on health?
- What is the country's capacity to adapt to climate change, for example,through modifications to the health infrastructure or by adopting specific adaptive measures?
- What essential knowledge gaps must be filled to fully understand the possible impacts of climate variability and change on human health?

These questions were developed to tailor the mandate of the National Assessment to the health sector. That mandate was to identify, for each particular sector or region 1) the current status;2) the expected impacts of climate variability and change;3) the adaptive capacity;and 4) the research gaps. Responding to these questions enabled assessment participants to evaluate a baseline and then to identify adaptation measures and research needs. Consistent with the National Assessment as a whole, the health sector did not address the question of the specific role of anthropogenic (human-caused) contributions to changes to climate or identify measures to reduce emissions of greenhouse gases or the presence of greenhouse gases in the atmosphere (e.g.,through carbon dioxide sequestration).These issues are critically important,and are the focus of other past and ongoing research and programs in the United States and elsewhere.However, the extent and success of current and future mitigation measures is uncertain.In addition, climate scientists project that some degree of projected climate change over the next several decades cannot be prevented,as a result of already elevated concentrations of greenhouse gases in the atmosphere, even if mitigation steps are taken.Thus,it is important to understand what adaptation measures might be desirable, or are feasible, regardless of mitigation, given the current climate projections.Future climate change assessments might choose to link adaptation and mitigation research and impacts.

## CONTEXT

Because human health is intricately bound to weather and the many complex natural systems it affects, it is possible that climate change as projected will have a measurable impact,both beneficial and adverse,on health outcomes associated with climate and/or weather (see Figure 1).These outcomes include temperature-related illnesses and deaths, injuries or fatalities from extreme weather events (i.e.,storms,tornadoes,hurricanes,and precipitation extremes),air pollution- related health effects,and diseases carried by water (water- and food-borne diseases) and by organisms such as mosquitoes, ticks,mites,and rodents (vector- and rodent-borne diseases).

To establish a baseline for projections of the potential impacts of climate on health, we reviewed the current status and context of health in the US,as reflected in indicators such as life expectancy and the leading causes of death.We also identified possible strains on public health and health care systems, such as cost and population growth.Urbanization, funding for public health infrastructure (e.g.,sanitation systems and medical research) and scientific developments contributed to advances in health status in the past and are expected to do so in the future.Environmental conditions,such as air and water quality, are important determinants of health.

Chronic diseases—heart disease,cancer, stroke,and chronic obstructive pulmonary disease are the leading four— accounted for almost 75% of all US deaths in 1996 for the 25- to 64- year old age group (NCHS,1998).Injuries and infectious diseases remain significant causes of morbidity and mortality in the US;infectious diseases caused one third of the deaths in the US in 1992,primarily because of respiratory tract infections,human immunodeficiency virus (HIV),and septicemia (Pinner et al.,1996). Patterns of illness and death vary substantially by socioeconomic status, geographic region, race, age,and gender (NCHS,1998).

Certain populations within the US — the poor, the elderly, children,and immunocompromised individuals — may be more vulnerable to many of the health risks that might be initially exacerbated by climate change. Poverty, for example,is a risk factor for heat-related illnesses and deaths,because the poor are more likely to live in urban areas and are less likely to be able to afford air-conditioning systems.Thus,making air-conditioned environments readily available to the poor is an adaptive response strategy to reduce illnesses and deaths in heat waves. Understanding what groups may be the most affected by climate change is critical to effective targeting of prevention or adaptation strategies. For example,air pollution and heat advisory warnings should specifically target children and the elderly, respectively.

It is also important to recognize that there are racial differences in health outcomes,including those associated with weather and/or climate,such as heat waves;these differences may be associated with poverty status,which is disproportionately high among African-Americans. For example,data on the 1995 heat wave in Chicago indicate that mortality among African-Americans was 50% higher than among whites (Whitman et al.,1997).The disparity likely reflects residence in inner- city neighborhoods, poverty, housing conditions,and medical conditions (Applegate et al.,1981; Jones et al.,1982;Kilbourne et al.,1982).

It is important to recognize that the proportion of elderly (65 years of age and older) and very elderly (85 years of age and older) residents is expected to rise in the coming decades.The proportion of the senior population in the very elderly category is growing fast:their numbers rose 274% between 1960 and 1994,while the entire US population grew only 45% (Hobbs and Damon,1998).Aging can be expected to be accompanied by multiple, chronic illnesses that may result in increased vulnerability to infectious disease or external/environmental stresses such as extreme heat (Hobbs and Damon,1998). Poverty, which increases with age in the elderly, may add to this vulnerability (Day, 1996).

**Potential Health Effects of Climate Variability and Change**

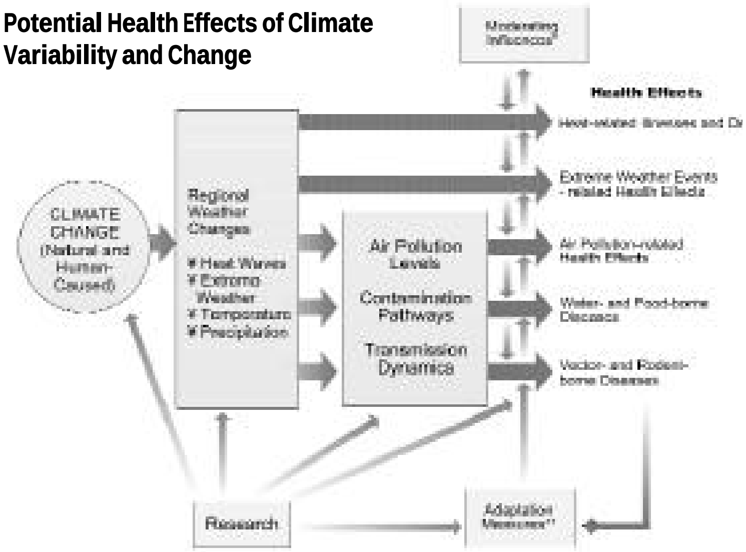


**Figure 1: Schematic diagram of the potential health effects of climate variability and change. (Source, Patz et al., 2000)**
*** Moderating influences include non-climate factors that affect climate-related health outcomes, such as: population growth and demographic change; standards of living; access to health care; improvements in health care; and public health infrastructure.**
**** Adaptation measures include actions to reduce risks of adverse health outcomes, such as: vaccination programs; disease surveillance; monitoring; use of protective technologies (e.g., air conditioning, pesticides, water filtration/treatment); use of climate forecasts; and development of weather warning systems; emergency management and disaster preparedness programs; and public education. See Color Figure Appendix**

Similarly, although the proportion of children younger than 5 years of age is not expected to grow as significantly as the proportion of the elderly, their number will increase even if immigration levels are kept constant.The variables that may affect children's special vulnerability to the possible impacts of climate change include:poverty [currently approximately 20% of US children are poor (NCHS, 1998)];access to medical care;and children's susceptibility to environmental hazards because of their size,behavior, and the fact that they are growing and developing (Landrigan et al.,1999).

Finally, it is anticipated that the proportion of immunocompromised people in the US may increase with the aging of the population and the success of medical treatments (e.g.,cancer therapy and HIV medications),but data are difficult to obtain. For example,survival has improved for acquired immunodeficiency syndrome (AIDS) patients, resulting in a 12% increase from 1996-1997 in the number of people living with AIDS (CDC, 1998).AIDS patients and other immunocompromised individuals may be more susceptible to waterborne and vector-borne pathogens,to the adverse impacts of exposure to elevated levels of certain air pollutants,and to debilitation due to physical stresses,such as those experienced during heat waves or in adverse emergency weather conditions,unless they can be adequately protected from those stresses with access to air conditioning,sanitation,safe water, and sufficient food.

## CLIMATE AND HUMAN HEALTH

The National Assessment climate models project that over the relevant time period the US climate will be characterized by increased temperatures,an altered hydrologic cycle,and increased variability. These projections are based in part on historical data;however, a detailed systematic record of weather parameters is only available for some places for approximately the last hundred years,although indirect measurements from ice cores,tree rings,other paleo-data and written history extend further (Houghton,1997).In the past 100 years,the global surface temperature has warmed between 0.7 and 1.4° F (Easterling et al.,1997; Jones et al.,1999;

### Table 1. Summary of the Health Sector Assessment

| Potential health impacts | Weather factors of interest * | Direction of possible change in health impact | Examples of some specific adaptation strategies | Priority research areas |
|---|---|---|---|---|
| Heat-related illnesses and deaths | Extreme heat and stagnant air masses | ↑ | Air conditioning<br>Early warning | Improved prediction, warning and response<br>Urban design and energy systems<br>Exposure assessment<br>Weather relationship to influenza and other causes of winter mortality |
| Winter deaths | Extreme cold<br>Snow<br>Ice | ↓ | | |
| Extreme weather events-related health effects | Precipitation variability (heavy rainfall events †)<br>Storms | ↑ | Early warning<br>Engineering<br>Zoning and building codes | Improved prediction, warning and response<br>Improved surveillance<br>Investigation of past impacts and effectiveness of warnings |
| Air pollution-related health effects | Temperature<br>Stagnant air masses | ↑ | Early warning<br>Mass transit<br>Urban planning<br>Pollution control | Relationships between weather and air pollution concentrations<br>Combined effects of temperature/humidity on air pollution<br>Effect of weather on vegetative emissions and allergens (e.g.,pollen) |
| Water- and food-borne diseases | Precipitation<br>Estuary water temperatures | ↑ | Surveillance<br>Improved water systems engineering | Improved monitoring effects of weather/environment on marine-related disease<br>Land use impacts on water quality (watershed protection)<br>Enhanced monitoring/mapping of fate and transport of contaminants |
| Vector- and rodent-borne diseases | Temperature<br>Precipitation variability<br>Relative humidity | ↑ ↓ | Surveillance<br>Vector control programs | Rapid diagnostic tests<br>Improved surveillance<br>Climate-related disease transmission dynamic studies |

* Based on projections provided by the National Assessment Synthesis Team.Other scenarios might yield different changes.
† Projected change in frequency of hurricanes and tornadoes is unknown.

NRC, 2000). In the contiguous US, temperatures have increased by approximately 1°F (Karl et al., 1996), and precipitation has been increasing in the US, with much of this change due to increases in heavy-precipitation events (> 2 inches [5 cm] per day) and decreases in light-precipitation events (Karl et al., 1995; Karl et al., 1996; Karl and Knight, 1998). These historical data are consistent with climate change theory that suggests an altered hydrological cycle accompanying warming of the Earth's surface (Fowler and Hennessey, 1995; Mearns et al., 1995; Trenberth, 1999).

We examined the impact of this projected climate change on five health outcomes: 1) temperature-related morbidity and mortality; 2) health effects of extreme weather events (i.e., storms, tornadoes, hurricanes, and precipitation extremes); 3) air pollution-related health effects; 4) water- and food-borne diseases; and 5) vector- and rodent-borne diseases. Some of these outcomes are relatively direct (e.g., effects of exposure to extreme heat or extreme events); others involve intermediate and multiple pathways, making assessments more challenging (see Figure 1).

Projections of the extent and direction of some potential health impacts of climate variability and change can be made, but there are many layers of uncertainty (see Table 1). First, methods to project changes in climate over time continue to improve, but climate models are unable to accurately project regional-scale impacts. Second, basic scientific information on the sensitivity of human health to aspects of weather and climate is limited. In addition, the vulnerability of a population to any health risk varies considerably depending on moderating factors such as population density, level of economic and technological development, local environmental conditions, preexisting health status, the quality and availability of health care, and the public health infrastructure.

It is also difficult to anticipate what adaptive measures might be taken in the future to mitigate risks of adverse health outcomes, such as vaccines, disease surveillance, protective technologies (e.g., air conditioning or water filtration/treatment), use of weather forecasts and warning systems, emergency management and disaster preparedness programs, and public education (see Figure 1). As they do currently, the need for and the success of adaptation measures can be expected to vary in different parts of the country—for example, Chicago must plan for heat waves, and communities along the southeast coast must be prepared for hurricanes. For the most part, government organizations fund public health systems within the US. Continued investments in advancing the public health infrastructure are crucial for adapting to the potential impacts of climate variability and change.

# KEY ISSUES

- Temperature-related illnesses and deaths
- Health effects related to extreme weather events
- Air pollution-related health effects
- Water- and food-borne diseases
- Insect-, tick-, and rodent-borne diseases

## 1. Temperature-related Illnesses and Deaths

Heat and heat waves are projected to increase in severity and frequency with increasing global mean

**July Heat Index Change - 21st Century**

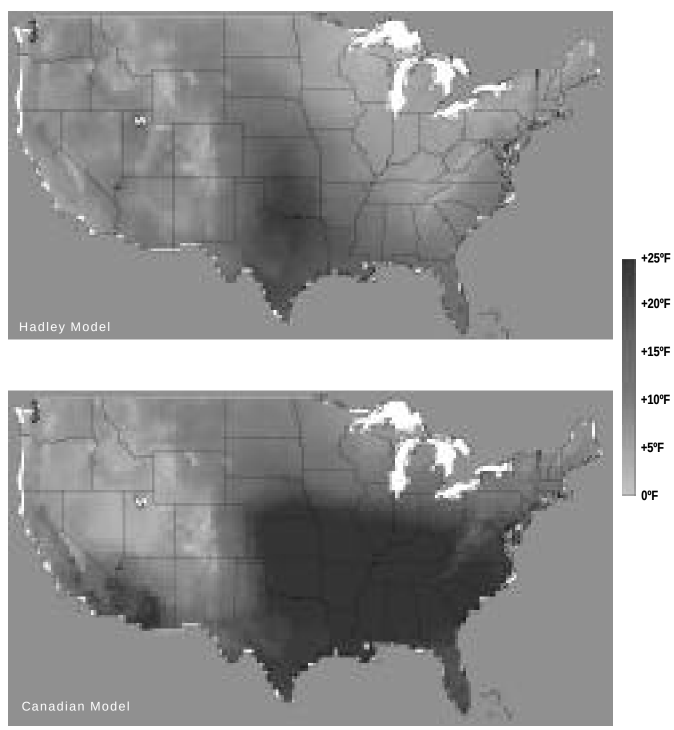


**Figure 2: Both models project substantial increases in the July heat index (which combines heat and humidity) over the 21st century. These maps show the projected increase in average daily July heat index relative to the present. The largest increases are in the southeastern states, where the Canadian model projects increases of more than 25°F. For example, a July day in Atlanta that now reaches a heat index of 105°F would reach a heat index of 115°F in the Hadley model, and 130°F in the Canadian model. (Map by Benjamin Felzer, UCAR, based on data from Canadian and Hadley modeling centers.) See Color Figure Appendix**

**Heat Related Deaths in Chicago in July 1995**

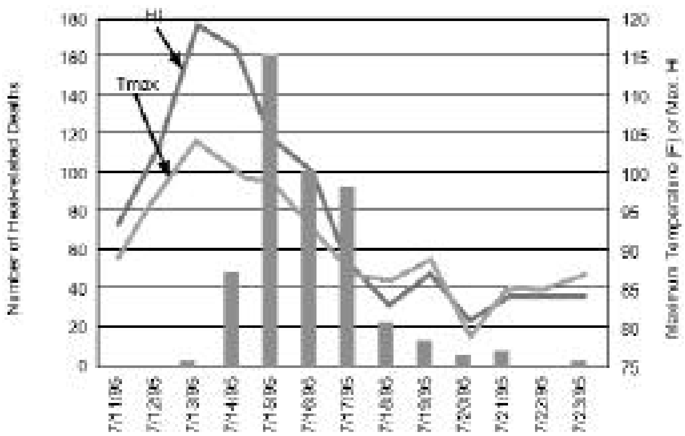


**Figure 3: This graph tracks the maximum temperature (Tmax), heat index (HI), and heat-related deaths in Chicago each day from July 11 to 23, 1995. The gray line shows maximum daily temperature, the blue line shows the heat index, and the bars indicate the number of deaths each day. (Source: NOAA/NCDC) See Color Figure Appendix**

temperatures (Meehl et al.,2000);see Figure 2. Studies of heat waves in urban areas have shown an association between increases in mortality and increases in heat,measured by maximum or minimum temperature,and heat index (a measure of temperature and humidity).Some of these studies adjust for other weather conditions (Semenza et al.,1996; Kalkstein and Greene,1997). For example,after a five-day heat wave in 1995 in which maximum temperatures in Chicago,Illinois ranged from 93°F to 104°F, the number of deaths increased 85% over the number recorded during the same period of the preceding year (CDC,1995);see Figure 3.At least 700 excess deaths (i.e.,deaths beyond those expected for that period in that population) were recorded,most of which were directly attributed to heat (CDC, 1995;Semenza et al.,1996;Semenza et al.,1999).

Exposure to extreme and prolonged heat is associated with heat cramps,heat syncope (fainting),heat exhaustion,and heat stroke.These health effects appear to be related to environmental temperatures above those to which the population is accustomed. Models of weather-mortality relationships indicate that populations in northeastern and midwestern US cities are likely to experience the greatest number of heat-related illnesses and deaths in response to changes in summer temperature, and that the most sensitive regions are those where extremely high temperatures occur infrequently or irregularly (Kalkstein and Smoyer, 1993);see Figure 4. For example,Philadelphia,Chicago,and Cincinnati have each experienced a heat wave that resulted in a large number of heat-related deaths.Physiologic and behavioral adaptations among vulnerable populations may reduce morbidity and mortality due to heat.Although long-term physiologic adaptation to heat events has not been documented,adaptation appears to occur as the summer season progresses; heat waves early in the summer often result in more deaths than subsequent heat waves or than those occurring later in the summer (Kalkstein and Smoyer, 1993).Heat waves are episodic,and although populations may adapt to gradual temperature increases,physiologic adaptation for extreme heat events is unlikely.

Within heat-sensitive regions,populations in urban areas are the most vulnerable to adverse heat- related health outcomes.Heat indices and heat-related mortality rates are higher in the urban core than in surrounding areas (Landsberg,1981).Urban areas retain heat throughout the nighttime more efficiently than do outlying suburban and rural areas (Buechley et al.,1972;Clarke,1972). The absence of nighttime relief from heat for urban inhabitants is a factor in excessive heat-related deaths.

The size of US cities and the proportion of US residents living in them are projected to increase over the next century, so it is possible that the population at risk for heat-related illnesses and deaths will increase.High-risk sub-populations include people who live in the top floors of apartment buildings in cities and who lack access to air-conditioned environments (either at home or elsewhere).The elderly (Ramlow and Kuller, 1990;CDC,1993;Whitman et al.,1997;Semenza,1999), young children (CDC, 1993),the poor (Schuman,1972;Applegate et al., 1981),and people who are bedridden or on medications that affect the body's thermoregulatory ability (Kilbourne et al.,1982;Di Maio and Di Maio,1993; Marzuk et al.,1998) are particularly vulnerable.

There is evidence that heat-related illnesses and deaths are largely preventable through behavioral adaptations,including the use of air conditioning and increased fluid intake (Kilbourne et al.,1982), although the magnitude of mortality reduction cannot be predicted.The proportion of housing units with central and/or room unit air conditioning ranges from below 30% in the Northeast to almost 90% in the South (Bureau of the Census,1997a).The use of air-conditioning systems in homes, workplaces,and vehicles has increased steadily over the past 30 years and is projected to become nearly universally available in the US by the year 2050 (Bureau of the Census,1997a;Bureau of the Census,1997b).

Overall death rates are higher in the winter than in the summer, and it is possible that milder winters could reduce deaths in winter months (Kalkstein and Greene,1997).However, the relationship between winter weather and mortality is difficult to interpret. For example,many winter deaths are due to infectious diseases such as influenza and pneumonia,and it is unclear how influenza transmission would be affected by higher winter temperatures.In addition,studies indicate an association between snowfall and fatal heart attacks (from winter precipitation rather than cold temperatures) (Spitalnic et al.,1996;Gorjanc et al.,1999).The net effect on winter mortality from climate change is therefore extremely uncertain,and the overall balance between changes in summer and winter weather-related deaths is unknown.

Beyond individual behavioral changes,adaptation measures include the development of community-wide heat emergency plans,improved heat warning systems,and better heat-related illness management plans.Research can refine each of these measures, including which weather parameters are most important in the weather-health relationship,the associations between heat and nonfatal illnesses,the evaluation of implemented heat response plans,and the effectiveness of urban design in reducing heat retention.

## 2. Health Effects Related to Extreme Weather Events

Climate change may alter the frequency, timing, intensity, and duration of extreme weather events (Fowler and Hennessey, 1995;Karl et al.,1995; Mearns et al.,1995),i.e.,meteorological events that have a significant impact on local communities. Increases in heavy precipitation have occurred over the past century (Karl et al.,1995;Karl and Knight, 1998).Future climate scenarios show likely increases in the frequency of extreme precipitation events, including precipitation during hurricanes (Knutson and Tuleya,1999).This poses an increased risk of floods (Meehl et al.,2000). Frequencies of tornadoes and hurricanes cannot reliably be projected.Whether these changes in climate risk result in increased health impacts cannot currently be assessed.

Injury and death are the direct health impacts most often associated with natural disasters. Secondary health effects have also been observed. These impacts are mediated by changes in ecological systems (such as bacterial and fungal proliferation) and public health infrastructures (such as the availability of safe drinking water).The health impacts of

**Average Summer Mortality Rates**

**Attributed to Hot Weather Episodes**

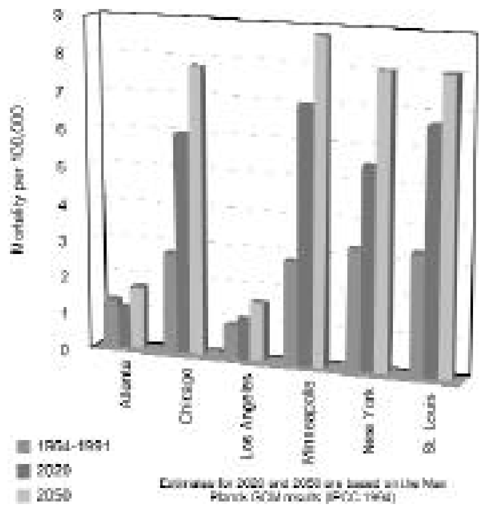


**Figure 4: Deaths due to summer heat are projected to increase in US cities, according to a study using time-dependent results ( for greenhouse gas increase only) from several climate models (Kalkstein and Greene, 1997). Mortality rates (number of deaths per 100,000 population) are shown from the Max Planck Institute model, the results from which lie roughly in the middle of the models examined (the other climate scenarios used were from Geophysical Fluid Dynamics Laboratory (GFDL) and the Hadley Centre). Because heat-related illness and death appear to be related to temperatures much hotter than those to which the population is accustomed, cities that experience extreme heat only infrequently appear to be at greatest risk. For example, Philadelphia, New York, Chicago, and St. Louis have experienced heat waves that resulted in a large number of heat-related deaths, while heat related deaths in Atlanta and Los Angeles are much lower. In this study, statistical relationships between heat waves and increased death rates are constructed for each city based on historical experience. Deaths under a city's future climate are then projected by applying that city's projected incidence of extreme heat waves to the statistical relationship that was estimated for the city whose present climate is most similar to the projected climate for the city in question. This approach attempts to represent how people will acclimate to the new average climate that they experience. See Color Figure Appendix**

extreme weather events such as floods and storms hinge on the vulnerabilities and recovery capacities of the natural environment and the local population. A community's level of preparedness greatly affects the severity of the health impacts of an extreme event.

From 1945 to 1989,145 natural disasters caused 14,536 deaths in the United States,an average of 323 deaths per year (Glickman and Silverman, 1992).According to the National Weather Service, severe storms caused 600 deaths and 3,799 reported injuries in 1997 (NWS,1999).Floods are the most frequent natural disaster and the leading cause of death from natural disasters in the US;the average annual loss of life is estimated to be as high as 146 deaths per year (NWS,1992).Hurricanes also pose an ongoing threat;an average of two each year make landfall on the US coastline (NWS,1993).The impacts of hurricanes include injuries and deaths resulting from strong winds and heavy rains.

Depending on the severity and nature of the weather event,people may experience disabling fear or aversion (Drabek,1996).There is controversy about the incidence and continuation of significant mental problems,such as post traumatic stress disorder (PTSD),after disasters (Quarantelli,1985).However, an increase in the number of mental disorders has been observed after several natural disasters in the US.Increased psychological problems were reported during a 5-year period after Hurricane Agnes caused widespread flooding in Pennsylvania in 1972 (Logue et al.,1979).More recently, a longitudinal study of local residents who lived through Hurricane Andrew showed that 20-30% of the adults in the area met the criteria for PTSD at 6 months and 2 years after the event (Norris et al.,1999).

A population's ability to minimize the potential health effects associated with extreme weather events is based on a number of diverse and interrelated factors including:building code regulations, warning systems,and disaster policies; evacuation plans;adequate relief efforts;and recovery (Noji, 1997).There are many federal,state,and local government agencies and nongovernmental organizations involved in planning for and responding to natural disasters in the US. For example,the Federal Emergency Management Agency (FEMA) recently launched its National Mitigation Strategy (FEMA, 1996),which is designed to increase public awareness of natural hazard risk and to reduce the risk of death,injury, community disruption,and economic loss.This strategy represents a comprehensive effort to address severe events with a series of initiatives and public-private partnerships.

Future research on extreme weather events and associated health effects should focus on improving climate models to project trends,if any, in regional extreme events.This type of improved prediction capability will assist in public health mitigation and preparedness.In addition,epidemiologic studies of health effects beyond the direct impacts of disaster will provide a more accurate measure of the full health impacts and will assist in planning and resource allocation.

## 3. Air Pollution-related Health Effects

Air pollutants have many sources—natural (e.g., vegetation and volcanoes), agricultural (e.g.,methane and pesticides),commercial (e.g.,dry cleaning operations and auto body shops),industrial (e.g.electric power plants and manufacturing facilities),transportation (e.g.truck and automobile emissions),and residential (e.g.home gas and oil burners and wood stoves).Ambient levels of regulated air pollutants (which include particulate matter, ozone,carbon monoxide,and sulfur and nitrogen oxides) have generally dropped since the mid-1970s,but air quality in many parts of the country falls short of health-based air quality standards.In 1997, about 107 million people in the US lived in counties that did not meet the air quality standards for at least one regulated pollutant (USEPA,1998a).

Air pollution is related to weather both directly and indirectly. Climate change may affect exposures to air pollutants by:1) affecting weather and thereby local and regional pollution concentrations (Penner et al.,1989;Robinson,1989);2) affecting human-caused emissions,including adaptive responses involving increased fuel combustion for power generation;3) affecting natural sources of air pollutant emissions (USEPA,1997a;USEPA,1998a);and 4) changing the distribution and types of airborne allergens (Ahlholm et al.,1998).Local weather patterns,including temperature,precipitation, clouds, atmospheric water vapor, wind speed,and wind direction influence atmospheric chemical reactions. They can also affect atmospheric transport processes and the rate of pollutant export from urban and regional environments to the global scale environments (Penner et al.,1989;Robinson,1989).In addition,the chemical composition of the atmosphere may in turn have a feedback effect on the local climate.

If the climate becomes warmer and more variable, air quality is likely to be affected. For example,if warmer temperatures lead to more air-conditioning use,power plant emissions could increase without additional air pollution controls.Analyses show that higher surface temperatures are conducive to the formation of ground-level ozone,particularly in urban areas (Morris et al.,1989;NRC,1991;Sillman and Samson,1995;USEPA,1996;USEPA,1998a);see Figure 5.

Changing weather patterns contribute to yearly differences in ozone concentrations (USEPA,1998a); for example,the hot,dry, stagnant meteorological conditions in 1995 in the central and eastern US were highly conducive to ozone formation.However, the specific type of change (i.e.,local, regional,or global),the direction of change in a particular location (i.e.,positive or negative),and the magnitude of change in air quality that may be attributable to climate change are not known.

Because the effect of climate change on all of the air pollutants of concern,especially particulate matter, is unknown,it is difficult to determine the overall effect of climate variability and change on respiratory health.Health effects associated with climate impacts on air pollution will depend on future air pollution levels.Since 1970,emissions and ambient air pollutants have declined overall (USEPA,1996). However, the majority of regulated air pollutants are from fossil fuel combustion (USEPA,1997a;USEPA, 1998a) and,as a result,increased energy and fuel-use would increase emissions of air pollutants without additional air pollutant controls.Integrated air quality modeling studies will be necessary to assess more quantitatively the potential health impacts of air quality changes associated with global climate change.These models would need to incorporate variables such as:1) future human-caused emissions (driven by economic growth,air pollution controls, vehicle usage,and possible changes in use of fuel for heating and cooling);2) future natural emissions (factoring in possible responses to changing climate);and 3) changes in local meteorology due to global climate change.

Current exposures to air pollutants have serious public health consequences.Ground-level ozone can exacerbate respiratory diseases by damaging lung tissue, reducing lung function,and sensitizing the lungs to other irritants (Romieu,1999).Short-term drops in lung function caused by ozone are often accompanied by chest pain,coughing,and pulmonary congestion (American Thoracic Society, 1996).Epidemiologic studies have found that exposure to particulate matter can aggravate existing respiratory and cardiovascular diseases,alter the body's defense systems against foreign materials,damage lung tissue,lead to premature death,and possibly contribute to cancer (American Thoracic Society, 1996;Lambert et al., 1998).Health effects of exposures to carbon monoxide,sulfur dioxide,and nitrogen dioxide can include reduced work capacity, aggravation of existing cardiovascular diseases,effects on respiratory function, respiratory illnesses,lung irritation,and alterations in the lung's defense systems (American Thoracic Society, 1996;Lambert et al.,1998).

**Maximum Daily Ozone Concentrations versus Maximum Daily Temperature in Atlanta and New York**

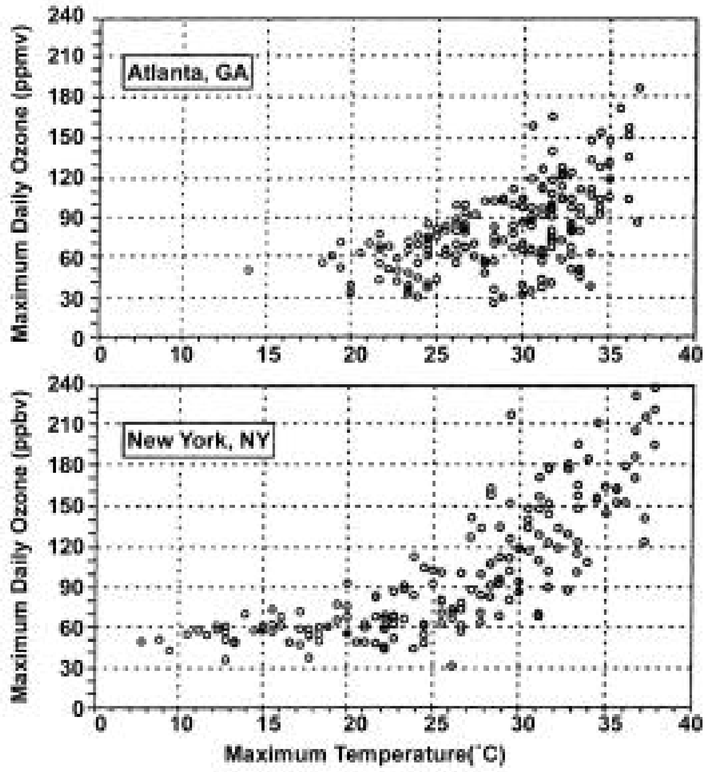


**Figure 5: These graphs illustrate the observed association between ground-level ozone concentrations and temperature in Atlanta and New York City (May to October 1988-1990). The projected higher temperature across the US in the 21st century will likely increase the occurrence of high ozone concentrations, especially because extremely hot days frequently have stagnant air circulation patterns, although this will also depend on emissions of ozone precursors and meteorological factors. Ground-level ozone can exacerbate respiratory diseases and cause short-term reductions in lung function. (Maximum Daily Ozone Chart provided by USEPA.) – See Color Figure Appendix**

In addition to affecting exposure to air pollutants (whether man-made or naturally emitted),there is some chance that climate change will play a role in human exposure to airborne allergens.Plant species are sensitive to weather, and climate change will possibly alter pollen production in some plants or the geographic distribution of plant species (Ahlholm et al.,1998).Consequently, there is some chance that climate change will affect the timing or duration of seasonal allergies,such as hay fever.The impact of pollen and of pollen changes on the occurrence and severity of asthma,the most common chronic disease of childhood,is currently very uncertain.

There is some chance that climate change will affect the amount of time individuals spend indoors (e.g., individuals may spend more time in air conditioned environments to avoid extreme heat,or may spend more time outdoors if winter temperatures are milder), resulting in changed exposure to indoor air pollutants and allergens.In some cases,these indoor environments may be more dangerous than the ambient conditions.

Adaptation measures include ensuring the responsiveness of federal and state air quality protection programs to changing pollution levels.These standards are designed to protect the public health by limiting emissions of key air pollutants and thus reducing ambient concentrations.The Pollutants Standards Index (Davies and Mazurek,1998),an EPA-coordinated health advisory system that provides warnings for both the general population and susceptible individuals,could be further strengthened for specific pollutants.

Future research in the area of health effects associated with air pollution should include:basic atmospheric science elucidating the association between weather, ozone,particulate matter, and other air pollutants and aeroallergens;improving existing models (e.g., expanding the spatial domain and lengthening the duration of modeled events) and their linkage with climate change scenarios;and closing the gaps in our understanding of common pollutants,such as particulate matter and ozone,and of individual exposures to these pollutants.

## 4. Water- and Food-borne Diseases

More than 200 million people in the US have direct access to treated public water supply systems, yet as many as 9 million annual cases of water-borne disease are estimated (Bennett et al.,1987);high uncertainty accompanies this estimate,and reporting is variable by state (Frost et al.,1996).Although most of these cases of water-borne disease involve mild gastrointestinal illnesses,other severe outcomes such as myocarditis (infection of the heart) are now recognized.These infections and illnesses can be chronic and even fatal in infants,the elderly, pregnant women,and people with weakened immune systems (Gerba et al.,1996;ASM,1998).

In the US, food-borne diseases are estimated to cause 76 million cases of illness,with 325,000 hospitalizations and 5,000 deaths per year (Mead et al., 1999).Microbiologic agents in water (e.g.,viruses, bacteria,and protozoa) can contaminate food (e.g. shellfish and fish).In addition,there have been instances of contamination of fresh fruits and vegetables by water-borne pathogens (Tauxe,1997).

The routes of exposure to water- and food-borne diseases include ingestion,inhalation,and dermal absorption of microbial organisms or algal toxins. For example,people can ingest water-borne microbiologic agents by drinking contaminated water, by eating seafood from contaminated waters,or by eating fresh produce irrigated or processed with contaminated water (Tauxe,1997).They also can be exposed by contact with contaminated water through commerce (e.g., fishing) or recreation (e.g., swimming) (Coye and Goldoft,1989).The water-borne pathogens of current concern include viruses,bacteria,and protozoa.Examples include *Vibrio vulnificus*, a naturally occurring estuarine bacterium responsible for a high percentage of the deaths associated with shellfish consumption (Johnston et al., 1985;Shapiro et al.,1998); *Cryptosporidium parvum* and *Giardia lamblia*, protozoa associated with gastrointestinal illnesses (Craun,1998);and biologic toxins associated with harmful algal blooms (Baden et al.,1996).Many of these were discovered only recently and are the subject of ongoing research.

Between 1980 and 1996,401 disease outbreaks associated with drinking water were reported,with more than 750,000 associated cases of disease (Craun,1998).More than 400,000 of those cases (including 54 deaths,primarily of individuals whose immune systems were compromised by HIV infection or other illness) occurred in a 1993 outbreak of *Cryptosporidiosis* that resulted from the contamination of the Milwaukee,Wisconsin, water supply (Hoxie et al.,1997).A contributing factor in the contamination,in addition to treatment system malfunctions, was heavy rainfall and runoff that resulted in a decline in the quality of raw surface water arriving at the Milwaukee drinking water plants (MacKenzie et al.,1994).Studies from other locations in the US found positive correlations between rainfall and *Cryptosporidium* oocyst and *Giardia* cyst concentrations in river water (Atherholt et al.,1998) and human disease outbreaks (Weniger et al.,1983; Curriero et al.,2001). Many water treatment facilities still have difficulty removing these pathogens.

Changes in precipitation,temperature,humidity, salinity, and wind have a measurable effect on the quality of water used for drinking, recreational and commercial use,and as a source of fish and shellfish (see Figure 6).Direct weather associations have been documented for water-borne disease agents such as *Vibrio* bacteria (Motes et al.,1998),viruses

(Lipp et al.,1999),and harmful algal blooms (Harvell et al.,1999).In Florida during the strong El Niño of 1997-1998,high precipitation and runoff greatly elevated the counts of fecal bacteria and infectious viruses in local coastal waters (Harvell et al.,1999).In Gulf Coast waters, *Vibrio vulnificus* bacteria are especially sensitive to water temperature,which dictates their seasonality and geographic distribution (Lipp and Rose, 1997;Motes et al.,1998).In addition,toxic red tides proliferate as seawater temperatures increase (Valiela,1984).Over the past twenty-five years along the East Coast, reports of marine-related illnesses increased in correlation with El Niño events (Harvell et al.,1999).

For many water-borne diseases,the management and disposal of sewage,biosolids and other animal wastes,and the protection of watersheds and fresh water flows are critical variables that impact water quality and the risk of water-borne disease (ASM,1998).In September, 1999,the largest reported water-borne associated outbreak of *Escherichia coli* 0157:H7 occurred at a fairground in the state of New York and was linked to contaminated well water (CDC,1999a).Heavy rains following a period of drought coincided with this major outbreak event (New York Department of Health,2000).The likelihood of this type of problem occurring could increase under conditions of high soil saturation that enhances the rapid transport of microbiologic organisms (Yates and Yates, 1988). Finally, many communities in the US continue to use combined sewer and storm water drainage systems (Figure 7). These systems may pose a health risk should the frequency or intensity of storms increase,because raw sewage bypasses treatment and is discharged into receiving surface waters during storms (Rose and Simonds, 1998).

Climate changes projected to occur in the next several decades,in particular the likely increase in extreme precipitation events,will probably raise the risk of contamination events.However, whether these increases materialize depends on policy responses and the level of maintenance or improvement of infrastructure.Current adaptations for assessing and preventing water-borne diseases include legal and administrative measures such as water safety criteria,monitoring requirements,and health outcome surveillance,as mandated under the Safe Drinking Water Act,with amendments in 1996 (USEPA,1997b).Recent legislative and regulatory attention has focused on improved treatment of surface water to address

**Seasonality of Shellfish Poisoning in Florida 1981-1994**

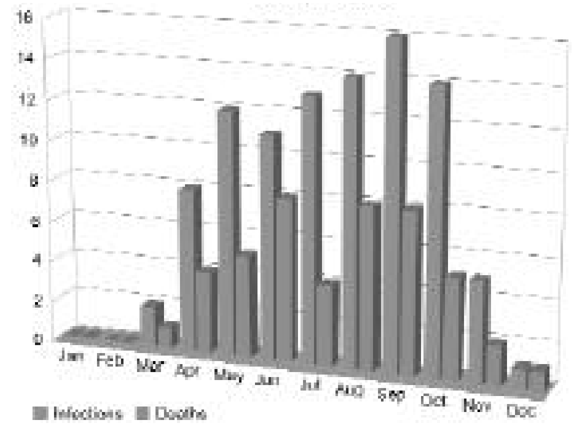


**Figure 6: Monthly distribution of oyster-associated Vibrio vulnificus illness (or shellfish poisoning) and deaths occurring in Florida from 1981-1994. Over the 14-year period, higher numbers of cases occur during summer. Monitoring in Florida shows a statistically significant association between concentrations of this pathogen in estuaries and temperature and salinity, the latter being affected by rainfall and runoff. (Adapted from: Lipp and Rose, 1997.) – See Color Figure Appendix**

**Locations of Combined Wastewater Systems**

**Figure 7: Wastewater systems that combine storm water drainage and sewage and industrial discharges are still in use in about 950 communities in the US, mostly in the Northeast and Great Lakes regions. These combined sewer systems deliver both storm drainage and wastewater to sewage treatment facilities. However, during rain or snowmelt, the volume of incoming water can exceed the capacity of the treatment system. Under those conditions, combined sewer systems are designed to overflow and discharge untreated wastewater into surface water bodies, and are termed as a combined sewer overflow (CSO) event. EPA, in 1994, developed a CSO Control Policy that sets forth a national framework for prevention of combined sewer overflows through the federal Clean Water Act's water discharge permit program. It has been suggested that if they continue to discharge untreated wastewater during storm events, combined sewer systems may pose a greater health risk should the frequency or intensity of storms increase. (Source: USEPA, http://www.epa.gov/owmitnet/cso.htm) See Color Figure Appendix**

microbial contaminants and on ground water and watershed protection (ASM,1998;USEPA,1998b).

With respect to marine-related human disease outbreaks,protection is provided by measures such as adequate sewage/sanitation systems and safe food storage infrastructures,and beach and recreational water monitoring (USEPA,1999).However, these measures are inadequate for microbial contaminants.With increasing trends in food importation, improved surveillance and preventive measures are required (Tauxe,1997),as well as a better understanding of how climate and weather might affect food and water safety outside the US.

Important knowledge gaps must be addressed to improve the assessment of the association of climate with water-borne disease issues.Determinants of transport and fate of microbial pollutants associated with rainfall and snowmelt are not well quantified. Further studies should address the influence of varying land use on the water quality in watersheds. For urban watersheds, much of the current annual load of contaminants is transported into fresh and marine water bodies during storm events. For these reasons, regional and even localized projections of changes in the intensity and frequency of storms and changes in land use are required for improving climate variability/health assessments.

Advances in monitoring are necessary to improve our knowledge base and enhance early warning and prevention capabilities. Application of existing technologies could be expanded,such as molecular fingerprinting to track contaminant sources (CDC, 1999b),improvement of monitoring systems (CDC, 1999c),and the use of satellite remote sensing used to detect coastal algal blooms (Gower, 1995). Coordination and integration of monitoring across the varying agencies responsible for water-borne, food-borne,and coastal surveillance systems could greatly enhance our knowledge and adaptive potential.

## 5. Insect-, Tick-, and Rodent-borne Diseases

Diseases transmitted between humans by blood-feeding arthropods (insects,ticks,and mites),such as plague,typhus,malaria, yellow fever, and dengue fever were once common in the US and Europe (Philip and Rozeboom,1973;Beneson,1995;Reiter, 1996).The ecology and transmission dynamics of these “vector-borne”infections are complex,and the factors that influence transmission are unique to each disease.It is not possible,therefore,to make broad generalizations on the effect of climate on vector-borne diseases (Reiter, 1996;Reiter, 2000). Many of these diseases are no longer present in the US,mainly because of changes in land use, agricultural methods, residential patterns,human behavior, and vector control.However, diseases that may be transmitted to humans from wild animals (zoonoses) continue to circulate in nature in many parts of the country. Humans can become infected with the pathogens that cause these diseases through transmission by insects or ticks. For example, Lyme disease,which is tick- borne,circulates among white-footed mice in woodland areas of the Mid-Atlantic,Northeast,upper Midwest and West Coast of the US,and humans acquire the pathogen when they are bitten by infected ticks (Gubler, 1998).Flea-borne plague incidence increased in conjunction with increasing rodent populations after unseasonal winter-spring precipitation in New Mexico (Parmenter et al.,1999).

Humans may also become infected with pathogens that cause zoonotic diseases by direct contact with the host animals or their body fluids,as occurs with Hantavirus Pulmonary Syndrome (HPS).Hantaviruses are carried by numerous rodent species and are transmitted to humans through contact with rodent urine,droppings,and saliva,or by inhaling aerosols of these products.In 1993,a previously undocumented hantavirus, *Sin Nombre*, emerged in the Four Corners region of the rural southwestern US,causing HPS (Schmaljohn and Hjelle 1997).As of June 2000,274 cases had been confirmed in the US,30 in Canada,and 475 in Central and South America.In the US,the mortality rate is currently 39% in otherwise healthy individuals (personal communication, James Mills,CDC).

The impact of weather on rodent populations may affect disease transmission.The Four Corners outbreak was attributed to an explosion in the mouse population caused by an increase in their food supply resulting from unusually prolonged rainfall associated with the 1991-1992 El Niño event (Engelthaler et al.,1999;Glass et al.,2000).

Flooding has also been associated with rodent-borne leptospirosis,as occurred in the 1995 epidemic in Nicaragua.A case-control study showed a 15-fold risk of disease associated with walking through flood waters (Trevejo et al.,1998).In Salvador, Brazil,a large epidemic of leptospirosis peaked two weeks after severe flooding in 1996 (Ko et al., 1999).Although leptospirosis cases are rare in the US,the disease is under-diagnosed (Demers et al., 1983),and the bacteria has been found in samples from both rats and children from surveys conducted in urban areas (Demers et al.,1983;Childs et al., 1992).

Changes in ecosystems and sociologic factors play a critical role in the occurrence of these diseases. For instance,the increasing numbers of cases and spread of Lyme disease in the US and Europe stemmed from the reversion of large tracts of agricultural land to woodland and the subsequent increase in mouse, deer, and tick populations,combined with the spread of residential areas into undeveloped areas and farmland (IOM,1992).

Most vector-borne diseases exhibit a distinct seasonal pattern,which clearly suggests that they are weather sensitive.Rainfall,temperature,and other weather variables affect in many ways both vectors and the pathogens they transmit.Rainfall may increase the abundance of some mosquitoes by increasing the number of their breeding sites (Reisen et al.,1995),but excessive rainfall can flush these habitats and thus destroy the mosquitoes in their aquatic larval stages.Increased humidity can extend vector survival times (Reisen et al.,1995). Dry conditions may eliminate the smaller breeding sites,such as ponds and puddles,but create productive new habitats as river flow is diminished.Thus, epidemics of malaria are associated with rainy periods in some parts of the world but with drought in others.High temperatures can increase the rate at which mosquitoes develop into adults,the rate of development of the pathogens in the mosquitoes (Watts et al.,1987),and feeding and egg-laying frequency.The key factor in transmission is the survival rate of the vector (Gilles,1993).Higher temperatures may increase or reduce survival rate,depending on the vector, its behavior, ecology, and many other factors.Thus,the probability of transmission may or may not be increased by higher temperatures.

In some cases,specific weather patterns over several seasons appear to be associated with increased transmission rates. For example,in the midwestern US,outbreaks of St.Louis encephalitis (SLE,a viral infection of birds that can also infect and cause disease in humans) appear to be associated with the sequence of warm, wet winters,cold springs,and hot dry summers (Monath,1980).The factors underlying this association are complex and require more investigation (Reeves and Hammon,1962;Reiter, 1988).

In the western US,one study (Reeves et al.,1994) predicted that a 5.5 to 9°F (3-5°C ) increase in average temperature may cause a northern shift in the distribution of both Western Equine Encephalitis (WEE) and SLE outbreaks,and a decreased range of WEE in southern California based on temperature sensitivity of both virus and mosquito carrier.

Many other factors are important in transmission dynamics. For example,dengue fever — a viral disease mainly transmitted by *Aedes aegypti*, a mosquito that is closely associated with human habitation — is greatly influenced by house structure,human behavior, and general socioeconomic conditions. There is a marked difference in the incidence of the disease above and below the US- Mexico border:in the period 1980-1996,43 cases were recorded in Texas,as compared to 50,333 reported cases in the three contiguous border states in Mexico; Figure 8 shows data updated through 1999 (Reiter, 2001).

The tremendous growth in international travel increases the risk of importation of vector-borne diseases,some of which can be transmitted locally under suitable circumstances at the right time of the year (Gubler, 1998). Key preventive measures must be directed both at protecting the increasing number of US travelers going to disease-endemic areas, as well as preventing importation of disease by US and non-US citizens.The recent importation of West Nile virus encephalitis into New York illustrates the continued need for vigilant surveillance for zoonotic

**Reported Cases of Dengue 1980-1999**

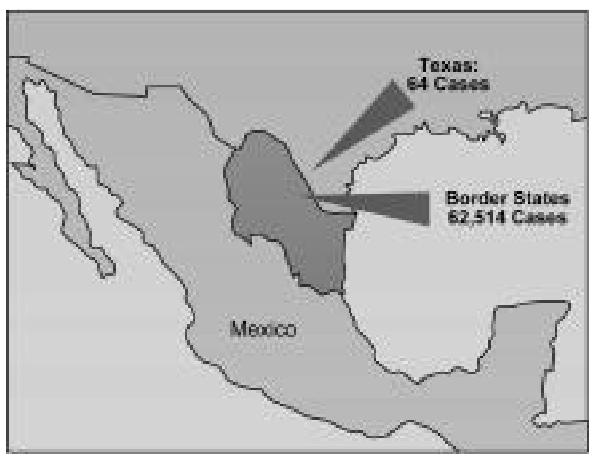


**Figure 8: Dengue along the US-Mexico border. Dengue, a mosquito-borne viral disease, was once common in Texas (where there were an estimated 500,000 cases in 1922), and the mosquito that transmits it remains abundant. The striking contrast in the incidence of dengue in Texas versus three Mexican states that border Texas (64 cases vs. 62,514) in the period from 1980-1999 provides a graphic illustration of the importance of factors other than temperature, such as use of air conditioning and window screens, in the transmission of vector-borne diseases. (National Institute of Health, Mexico; Texas Department of Health; US Public Health Service. Unpublished data.) – See Color Figure Appendix**

diseases potentially brought in by imported animals or international travelers (Lanciotti et al.,1999).An active survey in Florida recently documented under-reporting for some diseases,such as dengue fever (Gill et al.,2000),further demonstrating the need for improved surveillance to better estimate risk.

Preventive measures from these types of risks include vaccinations and drug prophylaxis for travelers,information for travelers,and the use of repellants and other protective measures.In the US,medical personnel should be made aware of this increased risk to travelers and of the need to improve surveillance of imported vector-borne diseases.

A high standard of living and well-developed public health infrastructure are central to the current capacity to adapt to changing risks of vector- and rodent-borne diseases in the US.Maintaining and improving this infrastructure—including surveillance,early warning,prevention,and control—remain a priority. Integration of climate,environmental,health,and socioeconomic data may facilitate implementing public health prevention measures. For example, climate forecasts can assist in disease prevention by predicting seasonal or interannual events such as El Niño,and early warning from improved vector and disease surveillance can help prevent local transmission of imported vector-borne diseases (Colwell and Patz,1998).

## ADDITIONAL ISSUES

Other health outcomes identified in the literature and by researchers as potentially affected by climate variability and change may warrant future study but are beyond the scope of this current assessment. For example, we did not address the potential impacts on health of economic losses or gains due to climate variability or attempt to assign a monetary value to the health outcomes of climate change. We did not address the potential impact that changes in the hydrologic cycle might have on crop production and food storage in the US (McMichael et al.,1996). Finally, we did not address stratospheric ozone depletion (McKenzie et al.,1999),although climate change may contribute to the delayed recovery of the stratospheric ozone hole (Shindell et al.,1998; Kirk-Davidoff et al.,1999),and possibly lead to adverse health impacts from increased UV exposure.

## ADAPTATION STRATEGIES

If climate change occurs as anticipated,it may have significant impacts on virtually all systems on which human life depends—biologic, hydrologic,and ecologic.The extent of the impacts that climate change may have on human health is very uncertain because it is dependent on multiple interrelated variables as well as on the condition of our public health infrastructure.Climate variability and change will likely have both positive and negative consequences for the health of the US population (see Table 2).

The future vulnerability of the US population to the health impacts of climate change depends on our capacity to adapt to potential adverse changes through legislative,administrative,institutional,technological,educational,and research-related measures.Examples include building codes and zoning to prevent storm or flood damage,severe weather warning systems,improved disease surveillance and prevention programs,improved sanitation systems, education of health professionals and the public, and research addressing key knowledge gaps in climate/health relationships.

Table 2: Human Health: Key Summary Messages

Multiple levels of uncertainty preclude any definitive statement on the direction of potential future change for each of the health outcomes assessed.

Although our report mainly addresses adverse health outcomes,some positive health outcomes were identified, notably reduced cold-weather mortality, which has not been extensively examined.

At present, much of the US population is protected against adverse health outcomes associated with weather and/or climate,although certain demographic and geographic populations are at increased risk.

Vigilance in the maintenance and improvement of public health systems and their responsiveness to changing climate conditions and to identified vulnerable subpopulations should help to protect the US population from adverse health outcomes of projected climate change.

## Table 3. Summary of Research Needs and Knowledge Gaps

| | |
|---|---|
| Temperature-related morbidity and mortality | Improvement of the early prediction of these events by determining the key weather parameters associated with health<br>Improvement of urban design to facilitate trees, shade, wind, and other heat-reducing conditions to limit the "urban heat island effect"<br>Better personal exposure assessment<br>Heat morbidity modeling<br>Understanding of weather relationship to causes of winter mortality |
| Extreme weather events–related health effects | Improvement of warning systems to provide early, easily understood messages to the populations most likely to be affected<br>Research on the effectiveness of educational materials and early warning systems<br>Long-term health effects from severe events, such as nutritional deficiency and mental health effects<br>Standardization of information collection after disasters to better measure morbidity and mortality<br>Effects of altered land use on vulnerability to extreme weather |
| Air pollution-related health effects | Association between weather and pollutants<br>Health impacts of chronic exposure to high levels of ozone<br>Health effects of exposure to ozone in people with asthma and other lung diseases<br>Interaction of ozone with other air pollutants<br>Mechanisms responsible for the adverse effects of air pollutants in the general population and within susceptible subgroups<br>Measures that can modulate the impact of air pollution on health, such as nutrition and other life-style characteristics<br>Urban weather modeling for inversions, etc. |
| Water- and food-borne diseases | Links between land use and water quality, through better assessment at the watershed level of the transport and fate of microbial pollutants associated with rain and snowmelt<br>Methods to improve surveillance and prevention of water-borne disease outbreaks<br>Epidemiologic studies<br>Molecular tracing of water-borne pathogens<br>Links between drinking water, recreational exposure, and food-borne disease monitoring<br>Links between marine ecology and toxic algae<br>Vulnerability assessment to improve water and waste water treatment systems |
| Vector- and rodent-borne diseases | Improvement of rapid diagnostic tests for pathogens<br>Vaccines<br>Improvement of active laboratory-based disease surveillance and prevention systems at the state and local level<br>Transmission dynamics (including reservoir host and vector ecology) studies<br>Improvement of surveillance systems for the arthropod vector and vertebrate hosts involved in the pathogen maintenance/transmission cycles to allow for more accurate predictive capability for epidemic/epizootic transmission<br>More effective and rapid electronic exchange of surveillance data |

Many of these adaptive responses are desirable from a public health perspective irrespective of climate change. For example, reducing air pollution obviously has both short- and long-term health benefits. Improving warning systems for extreme weather events and eliminating existing combined sewer and storm water drainage systems are other measures that can ameliorate some of the potential adverse impacts of current climate extremes and of the possible impacts of climate change. Improved disease surveillance and prevention systems at the state and local levels are already needed. Adaptation is a complex undertaking, as demonstrated by the varying degrees of effectiveness of current efforts to cope with climate variability. Considerable work still needs to be done to assess the feasibility (e.g., ability of a community to incur the costs) and the effectiveness of alternative adaptive responses, and to develop improved mechanisms for coping with climate variability and change.

## CRUCIAL UNKNOWNS/ RESEARCH NEEDS

We are still learning about the linkages between weather and human health in the present, even as we try to anticipate the health effects of climate variability and change in the future.(Specific knowledge gaps are discussed in the Health Sector report, in press,and are listed in Table 3.)

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