Synthesis and Assessment Product 4.6

Chapter 2: Effects of Global Change on Human Health

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Table of Contents

2.1 Introduction

Climate change can affect health directly and indirectly. Directly, extreme weather events (floods, droughts, windstorms, fires, and heatwaves) can affect the health of Americans and cause significant economic impacts. Indirectly, climate change can alter or disrupt natural systems, making it possible for vector, water-, and foodborne diseases to spread or emerge in areas where they had been limited or not existed, or for such diseases to disappear by making areas less hospitable to the vector or pathogen (NRC, 2001).

Climate also can affect the incidence of diseases associated with air pollutants and aeroallergens.[1] (Bernard *et al.,* 2001) The cause-and-effect chain from climate change to changing patterns of health outcomes is often complex and includes factors such as initial health status, financial resources, effectiveness of public health programs, and access to medical care. Therefore, the severity of future impacts will be determined by changes in climate as well as by concurrent changes in nonclimatic factors and by adaptations implemented to reduce negative impacts.

A comprehensive assessment of the potential impacts of climate change on human health in the United States was published in 2000. This First National Assessment was undertaken by the U.S. Global Change Research Program. The Health Sector Assessment examined potential impacts and identified research and data gaps to be addressed in future research; results appeared in a special issue of *Environmental Health Perspectives* (May 2001). The Health Sector Assessment's conclusions on the potential health impacts of climate change in the United States included:

- Populations in Northeastern and Midwestern U.S. cities are likely to experience the greatest number of illnesses and deaths in response to changes in summer temperatures (McGeehin and Mirabelli, 2001).
- The health impacts of extreme weather events hinge on the vulnerabilities and recovery capabilities of the natural environment and the local population (Greenough *et al.*, 2001).
- If the climate becomes warmer and more variable, air quality is likely to be affected (Bernard *et al.*, 2001). However, uncertainties in climate models make the direction and degree of change speculative (Bernard and Ebi, 2001).
- Federal and state laws and regulatory programs protect much of the U.S. population from waterborne disease. However, if climate variability increases, current and future deficiencies in areas such as watershed protection, infrastructure, and storm drainage systems will probably increase the risk of contamination events (Rose *et al.,* 2000).
- It is unlikely that vector- and rodent-borne diseases will cause major epidemics in the United States if the public health infrastructure is maintained and improved (Gubler *et al.,* 2001).
- Multiple uncertainties preclude any definitive statement on the direction of potential future change for each of the health outcomes assessed (Patz *et al.,* 2000).

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[1] Any of various airborne substances, such as pollen or spores, that can cause an allergic response.

The assessment further concluded that much of the U.S. population is protected against adverse health outcomes associated with weather and/or climate by existing public health and medical care systems, although certain populations are at increased risk.

This chapter of Synthesis Assessment Product 4.6 updates the Health Sector Assessment. It also examines adaptation strategies that have been or are expected to be developed by the public health community in response to the challenges and opportunities posed by climate change. The first section of this chapter focuses on climate-related impacts on human morbidity and mortality from extreme weather, vector-, water- and foodborne diseases, and changes in air quality. For each health endpoint, the assessment addresses the potential impacts, populations that are particularly vulnerable, and research and data gaps that, if bridged, would allow significant advances in future assessments of the health impacts of global change. The assessment includes research published from 2001 through early 2007 in the United States or in Canada, Europe, and Australia, where results may provide insights for U.S. populations.

This chapter summarizes the current burden of climate-sensitive health determinants and outcomes for the United States, before assessing the potential health impacts of climate change. Two types of studies are assessed. Studies that increase our understanding of the associations between weather variables and health outcomes raise possible concerns about the impacts of a changing climate. A few studies project the burden of health outcomes using scenarios of socioeconomic and climate change.

It is important to note that the assessment focuses on how climate change could affect the future health of Americans. However, the net impact of any changes will depend on many other factors, including demographics; population and regional vulnerabilities; the future social, economic, and cultural context; availability of resources and technological options; built and natural environments; public health infrastructure; and the availability and quality of health and social services.

The chapter then turns to adaptation to the potential health impacts of environmental change in the United States. It also considers public health interventions (including prevention, response, and treatment strategies) that could be revised, supplemented, or implemented to protect human health in response to the challenges and opportunities posed by global change; and how much adaptation could achieve.

2.2 Observed Climate-Sensitive Health Outcomes in the United States

2.2.1 Thermal Extremes: Heat Waves

Excess deaths occur during heatwaves, on days with higher-than-average temperatures, and in places where summer temperatures vary more or where extreme heat is rare (Braga *et al.*, 2001). Figure 2.1 illustrates that the relation between temperature and mortality is nonlinear, typically J- or U-shaped, and that increases in mortality occur even below temperatures considered to be extremely hot. This figure was created using log-linear regression to analyze 22 years of data on daily mortality and outdoor temperature in eleven U.S. cities (Curriero *et al.*, 2002). Exposure to excessive natural heat caused a reported 4,780 deaths during the period 1979 to 2002, and an additional 1,203 deaths had hyperthermia reported as a contributing factor (CDC, 2005). These numbers are underestimates of the total mortality associated with heatwaves because the person filling out the death certificate may not always list heat as a cause. Furthermore, heat can exacerbate chronic health conditions, and several analyses have reported associations with cause-specific mortality, including cardiovascular, renal, and respiratory diseases; diabetes; nervous system disorders; and other causes not specifically described as heat-related (Conti *et al.*, 2007; Fouillet *et al.*, 2006; Medina-Ramon *et al.*, 2006). Among the most well-documented heatwaves in the United States are those that occurred in 1980 (St. Louis and Kansas City, Missouri), 1995 (Chicago, Illinois), and 1999 (Cincinnati, Ohio; Philadelphia, Pennsylvania; and Chicago, Illinois). The highest death rates in these heatwaves occurred in people over 65 years of age.

Less information exists on temperature-related morbidity, and those studies that have examined hospital admissions and temperature have not seen consistent effects, either by cause or by demonstrated coherence with mortality effects where both deaths and hospitalizations were examined simultaneously (Kovats *et al.*, 2004; Michelozzi *et al.*, 2006; Schwartz *et al.*, 2004; Semenza *et al.*, 1999).

Age, fitness, body composition, and level of activity are important determinants of how the human body responds to exposure to thermal extremes (DeGroot *et al.*, 2006; Havenith *et al.*, 1995; Havenith *et al.*, 1998; Havenith, 2001). Groups particularly vulnerable to heat-related mortality include the elderly, very young, city-dwellers, those with less education, people on medications such as diuretics, the socially isolated, the mentally ill, those lacking access to air conditioning, and outdoor laborers (Diaz *et al.*, 2002; Klinenberg, 2002; McGeehin and Mirabelli, 2001; Semenza *et al.*, 1996; Whitman *et al.*, 1997; Basu *et al.*, 2005; Gouveia *et al.*, 2003; Greenberg *et al.*, 1983; O'Neill *et al.*, 2003; Schwartz, 2005; Jones *et al.*, 1982; Kovats *et al.*, 2004; Schwartz *et al.*, 2004; Semenza *et al.*, 1999; Watkins *et al.*, 2001). A sociological analysis of the 1995 Chicago heatwave found that people living in neighborhoods without public gathering places and active street life were at higher risk, highlighting the important role that community and societal characteristics can play in determining vulnerability (Klinenberg, 2002).

Figure 2.1 Temperature-mortality relative risk functions for 11 U.S. cities, 1973–1994. Northern cities: Boston, Massachusetts; Chicago, Illinois; New York, New York; Philadelphia, Pennsylvania; Baltimore, Maryland; and Washington, DC. Southern cities: Charlotte, North Carolina; Atlanta, Georgia; Jacksonville, Florida; Tampa, Florida; and Miami, Florida. Relative risk is defined as the risk of an event such as mortality relative to exposure, such that the relative risk is a ratio of the probability of the event occurring in the exposed group versus the probability of occurrence in the control (non-exposed) group.

Urban heat islands may increase heat-related health impacts by raising air temperatures in cities 2-10^{o}F over the surrounding suburban and rural areas due to absorption of heat by dark paved surfaces and buildings, lack of vegetation and trees, heat emitted from buildings, vehicles, and air conditioners, and reduced air flow around buildings (EPA, 2005; Pinho and Orgaz, 2000; Vose *et al.*, 2004; Xu and Chen, 2004). However, in some regions, urban areas may not experience greater heat-related mortality than in rural areas (Sheridan and Dolney, 2003); few comparisons of this nature have been published.

The health impacts of high temperatures and high air pollution can interact, with the extent of interaction varying by location (Bates, 2005; Goodman *et al.,* 2004; Goodman *et al.,* 2004; Keatinge and Donaldson, 2001; O'Neill *et al.,* 2005; Ren *et al.,* 2006).

2.2.2 Thermal Extremes: Cold Waves

From 1979 to 2002, an average of 689 reported deaths per year (range 417-1,021), totaling 16,555 over the period, were attributed to exposure to excessive cold temperatures (Fallico *et al.*, 2005). Cold also contributes to deaths caused by respiratory and cardiovascular diseases, so the overall mortality burden is likely underestimated. Factors associated with increased vulnerability to cold include black race (Fallico *et al.*, 2005); living in Alaska, New Mexico, North Dakota, and Montana, or living in milder states that experience rapid temperature changes (North and South Carolina) and western states with greater ranges in nighttime temperatures (*e.g.,* Arizona) (Fallico *et al.*, 2005); having less education (O'Neill *et al.,* 2003); being female or having pre-existing respiratory illness (Wilkinson *et al.,* 2004); lack of protective clothing (Donaldson *et al.*, 2001); income inequality, fuel poverty, and low residential thermal standards (Healy, 2003); and living in nursing homes (Hajat *et al.*, 2007).

Because climate change is projected to reduce the severity and length of the winter season (IPCC, 2007a), there is considerable speculation concerning the balance of climate change-related decreases in winter mortality compared with increases in summer mortality. Net changes in mortality are difficult to estimate because, in part, much depends on complexities in the relationship between mortality and the changes associated with global change. Few studies have attempted to link the epidemiological findings to climate scenarios for the United States, and studies that have done so have focused on the effects of changes in average temperature, with results dependent on climate scenarios and assumptions of future adaptation. Moreover, many factors contribute to winter mortality, making highly uncertain how climate change could affect mortality. No projections have been published for the United States that incorporate critical factors, such as the influence of influenza outbreaks.

2.2.3 Extreme Events: Hurricanes, Floods, and Wildfires

The United States experiences a wide range of extreme weather events, including hurricanes, floods, tornadoes, blizzards, windstorms, and drought. Other extreme events, such as wildfires, are strongly influenced by meteorological conditions. Direct morbidity and mortality due to an event increase with the intensity and duration of the event, and can decrease with advance warning and preparation. Health also can be affected indirectly. Examples include carbon monoxide poisonings from portable electric generator use following hurricanes (CDC, 2006b) and an increase in gastroenteritis cases among hurricane evacuees (CDC, 2005a). The mental health impacts (e.g., post traumatic stress disorder, depression) of these events are likely to be especially important, but are difficult to assess (Middleton *et al.*, 2002; Russoniello *et al.*, 2002; Verger *et al.*, 2003; North *et al.*, 2004; Fried *et al.*, 2005; Weisler *et al.*, 2006). However, failure to fully account for direct and indirect health impacts may result in inadequate preparation for and response to future extreme weather events.

Figure 2.2 shows the annual number of deaths attributable to hurricanes in the United States from the 1900 Galveston storm, (NOAA, 2006), records for the years 1940-2004 (NOAA, 2005a), and a summary of a subset of the 2005 hurricanes (NOAA, 2007). The data shown are dominated by the 1900 Galveston storm and a subset of 2005 hurricanes, particularly Katrina and Rita, which together accounted for 1,833 of the 2,002 lives lost to hurricanes in 2005 (NOAA, 2007b). While Katrina was a Category 3 hurricane and its path was forecast well in advance, there was a secondary failure of the levee system. This illustrates that multiple factors contribute to making a disaster and that adaptation measures may not fully avert adverse consequences.

From 1940 through 2005 roughly 4,300 lives were lost in the United States to hurricanes. The impact of the 2005 hurricane season is especially notable as it doubled the estimate of the average number of lives lost to hurricanes in the United States over the previous 65 years.

Figure 2.2 Annual Deaths Attributed to Hurricanes in the United States, 1900 and 1940-2005

Figure 2.3 shows the annual number of deaths attributed to flooding in the United States from 1940-2005 (NOAA, 2007a). Over this period roughly 7,000 lives were lost.

Figure 2.3 Annual Deaths Attributed to Flooding in the United States, 1940-2005

A wildfire's health risk is largely a function of the population in the affected area and the speed and intensity with which the wildfire moves through those areas. Wildfires can increase eye and respiratory illnesses due to fire-related air pollution. Climate conditions affect wildfire incidence and severity in the West (Westerling *et al.*, 2003; Gedalof *et al.*, 2005; Sibold and Veblen, 2006). Between 1987-2003 and 1970-1986, there was a nearly fourfold increase in the incidence of large Western wildfires (*i.e.*, fires that burned at least 400 hectares) (Westerling *et al.*, 2006). The key driver of this increase was an average increase in springtime temperature of 0.87°C that affected spring snowmelt, subsequent potential for evapotranspiration, loss of soil moisture, and drying of fuels (Running, 2006; Westerling *et al.*, 2006). Data providing a time-series summary of deaths similar to the data in Figures 2.2 and 2.3 was not identified.

There is a rich body of literature detailing the mental health impacts of extreme weather events. Anxiety and depression, the most common mental health disorders, can be directly attributable to the experience of the event (*i.e.*, being flooded) or indirectly during the recovery process (*e.g.*, Gerrity and Flynn, 1997). These psychological effects tend to be much longer lasting and can be worse than the physical effects experienced during an event and its immediate aftermath.

Extreme events are often multi-strike stressors, with stress associated with the event itself; the disruption and problems of the recovery period; and the worry or anxiety about the risk of recurrence of the event (Tapsell *et al.,* 2002). During the recovery period, mental health problems can arise from the problems associated with geographic displacement, damage to the home or loss of familiar possessions, and stress involved with the process of repairing. The full impact often is not appreciated until after people's homes have been put back in order. For instance, in the aftermath of Hurricane Katrina in 2005, mental health services in New Orleans were challenged by an increased incidence of serious mental illness, including anxiety, major depression, and post-traumatic stress disorder (PTSD). Shortly after Katrina, a Centers for Disease Control and Prevention poll found that nearly half of all survey respondents indicated a need for mental health care, yet less than 2% were receiving professional attention (Weisler *et al.*, 2006).

2.2.4 Indirect Health Impacts of Climate Change

The observation that most vector-, water- or foodborne and/or animal-associated diseases exhibit a distinct seasonal pattern suggests *a priori* that weather and/or climate influence their distribution and incidence. The following sections differentiate between zoonotic and water- and foodborne diseases, although many water- and foodborne diseases are zoonotic.

2.2.4.1 Vectorborne and Zoonotic (VBZ) Diseases

Transmission of infectious agents by blood-feeding arthropods (particular insect or tick species) and/or by non-human vertebrates (certain rodents, canids, and other mammals) has changed significantly in the United States during the past century. Diseases such as rabies and cholera have become less widespread and diseases such as typhus, malaria, yellow fever, and dengue fever have largely disappeared, primarily because of environmental modification and/or socioeconomic development (Philip and Bozeboom, 1973; Beneson, 1995; Reiter, 1996). While increasing average temperatures may allow the permissive range for *Aedes aegypti,* the mosquito vector of dengue virus, to move further north in the US, it is unlikely that more cases of dengue fever will be observed because most people are protected while living indoors due to quality housing. Indeed, a recent epidemic of dengue in southern Texas and northern Mexico produced many cases among the relatively poor Mexicans, and very few cases among Texans (Reiter *et al.*, 1999). At the same time, other diseases reported their distribution either because of suitable environmental conditions (including climate) or enhanced detection (examples include Lyme disease, ehrlichioses, and Hantavirus pulmonary syndrome) or were introduced and are expanding their range due to appropriate climatic and ecosystem conditions (West Nile Virus; *e.g.*, Reisen *et al.*, 2006). Still others are associated with non-human vertebrates that have complex associations with climate variability and human disease (*e.g.,* plague, influenza). The burden of VBZ diseases in the United States is not negligible and may grow in the future because the forces underlying VBZ disease risk simultaneously involve weather/climate, ecosystem change, social and behavioral factors, and larger political-economic forces that are part of globalization. In addition, introduction of pathogens from other regions of the world is a very real threat.

Few original research articles on climate and VBZ diseases have been published in the United States and in other developed temperate countries since the First National Assessment. Overall, these studies provide evidence that climate affects the abundance and distributions of vectors that may carry West Nile virus, Western Equine encephalitis, Eastern Equine encephalitis, Bluetongue virus, and Lyme disease. Climate also may affect disease risk, but sometimes in counter-intuitive ways that do not necessarily translate to increased disease incidence (Wegbreit and Reisen, 2000; Subak, 2003; McCabe and Bunnell, 2004; DeGaetano, 2005; Purse *et al.*, 2005; Kunkel *et al.*, 2006; Ostfeld *et al.*, 2006; Shone *et al.*, 2006). Changes in other factors such as hosts, habitats, and human behavior are also important.

2.2.4.2 Waterborne and Foodborne Diseases

Water and foodborne diseases continue to cause significant morbidity in the United States. In 2002, there were 1,330 food-related disease outbreaks (Lynch *et al.*, 2006), 34 outbreaks from recreational water (2004), and 30 outbreaks from drinking water (2004) (Dziuban *et al.*, 2006; Liang *et al.*, 2006). For outbreaks of foodborne disease with known etiology, bacteria (*Salmonella*) accounted for 55% and viruses accounted for 33% (Lynch *et al.*, 2006). Viral associated outbreaks rose from 16% in 1998 to 42% in 2002, primarily due to increases in norovirus (Lynch *et al.*, 2006). In recreational water, bacteria accounted for 32% of outbreaks, parasites (primarily *Cryptosporidium*) for 24%, and viruses 10% (Dziuban *et al.*, 2006). Similarly in drinking water outbreaks of known etiology, bacteria were the most commonly identified agent (29%, primarily *Campylobacter*), followed by parasites and viruses (each identified 5% of the time) (2003 – 2004; Liang *et al.*, 2006). Gastroenteritis continues to be the primary disease associated with food and water exposure. In 2003 and 2004, gastroenteritis was noted in 48% and 68% of reported recreational and drinking water outbreaks, respectively (Dziuban *et al.*, 2006; Liang *et al.*, 2006).

Water- and foodborne disease remain highly underreported (*e.g.*, Mead *et al.*, 1999). Few people seek medical attention and of those that do, few cases are diagnosed (many pathogens are difficult to detect and identify in stool samples) or reported. Using a combination of underreporting estimates, passive and active surveillance data, and hospital discharge data, Mead *et al.* (1999) estimated that over 210 million cases of gastroenteritis occur annually in the United States, including over 900,000 hospitalizations and over 6,000 deaths. More recently, Herikstad *et al.* (2002) estimated as many as 375 million episodes of diarrhea occur annually in the United States, based on a self-reporting study. These numbers far exceed previous estimates. Of the total estimated annual cases, just over 39 million can be attributed to a specific pathogen and approximately 14 million are transmitted by food (Mead *et al.*, 1999). While bacteria continue to cause the majority of documented foodborne and waterborne outbreaks (Lynch *et al.*, 2006; Liang *et al.*, 2006), the majority of sporadic (non outbreak) cases of disease are caused by viruses (67%; primarily noroviruses), followed by bacteria (30%, primarily *Campylobacter* and *Salmonella*) and parasites (3%, primarily *Giardia* and *Cryptosporidium*). While the outcome of many gastrointestinal diseases is mild and self limiting, they can be fatal or significantly decrease fitness in vulnerable populations, including young children, the immunocompromised, and the elderly. Children ages 1-4 and older adults (>80 years) each make up more than 25% of hospitalizations involving gastroenteritis, but older adults contributed to 85% of the associated deaths (Gangarosa *et al.*, 1992). As the U.S. population ages, the economic and public health burden of diarrheal disease will increase proportionally without appropriate interventions.

Most pathogens of concern for food- and waterborne exposure are enteric and transmitted by the fecal-oral route. Climate may affect the pathogen directly by influencing its growth, survival, persistence, transmission, or virulence. In addition, there may be important interactions between land-use practices and climate variability. For example, incidence of foodborne disease associated with fresh produce is growing (FDA, 2001; Powell and Chapman, 2007). Storm events and flooding may result in the contamination of food crops (especially produce such as leafy greens and tomatoes) with feces from nearby livestock or feral animals. Therefore, changing climate or environments may alter the transmission of pathogens or affect the ecology and/or habitat of zoonotic reservoirs (NAS, 2001)

Studies in North America (United States and Canada) (Fleury *et al.*, 2006; Naumova *et al.*, 2006), Australia (D'Souza *et al.*, 2004), and several countries across Europe (Kovats *et al.*, 2004a) report striking similarities in correlations between peak ambient temperatures (controlled for season) and peak in clinical cases of salmonellosis. Over this broad geographic range, yearly peaks in salmonellosis cases occur within 1 to 6 weeks of the highest reported ambient temperatures. Mechanisms suggested include replication in food products at various stages of processing (D'Souza *et al.*, 2004; Naumova *et al.*, 2006) and changes in eating habits during warm summer months (*i.e.*, outdoor eating) (Fleury *et al.*, 2006). Additionally, because *Salmonella* are well adapted to both host conditions and the environment, they can grow readily even under low nutrient conditions at warm temperatures (*e.g.*, in water and associated with fruits and vegetables) (Zhuang *et al.*, 1995; Mouslim *et al.*, 2002). Evidence supports the notion that increasing global temperatures will likely increase rates of salmonellosis; however, additional research is needed to determine the critical drivers behind this trend (*i.e.*, intrinsic properties of the pathogen or extrinsic factors related to human behavior).

The possible effects of increasing temperatures on *Campylobacter* infection rates and patterns cannot be reliably projected. The apparent seasonality of campylobacteriosis incidence is more variable than salmonellosis and temperature models are less consistent in their ability to account for the observed infection patterns. In the northeastern United States, Canada, and the U.K., *Camplyobacter* infection peaks coincide with high annual daily or weekly temperatures (Louis *et al.*, 2005; Fleury *et al.*, 2006; Naumova *et al.*, 2006). However, in several other European countries, campylobacteriosis rates peak earlier, before high annual temperatures, and in those cases temperature accounts for only 4% of the interannual variability (Kovats, *et al.*, 2005). Pathogenic species of *Campylobacter* cannot replicate in the environment and will not persist long under non-microaerophilic conditions, suggesting that high ambient temperatures would not contribute to increased replication in water or in food products.

Leptospirosis is a re-emerging disease in the United States and, given its wide case distribution, high number of pathogenic strains and wide array of hosts, it is often cited as one of the most widespread zoonotic disease in the world (Meites *et al.,* 2004; WHO, 1999). While it has not been a reportable disease nationally since 1995, several states continue to collect passive surveillance data and cases continue to be reported (Katz *et al.,* 2002; Meites *et al.,* 2004). Because increased disease rates are linked to warm temperatures, epidemiological evidence suggest that climate change may increase the number of cases.

Pathogenic species of *Vibrio* (primarily *V. vulnificus*) account for 20% of sporadic shellfish-related illnesses and over 95% of deaths (Lipp and Rose 1997; Morris, 2003). While the overall incidence of illness from *Vibrio* infections remains low, the rate of infection increased 41% since 1996 (Vugia *et al.*, 2006). *Vibrio* species are more frequently associated with warm climates (*e.g.,* Janda *et al.,* 1988; Lipp *et al.,* 2002). Coincident with proliferation in the environment, human cases also occur during warm temperatures. In the US, the highest case rates occur in the summer months (Dziuban *et al.,* 2006). Given the close association between temperature, the pathogen, and disease, increasing temperatures may increase the geographic range and disease burdens of *Vibrio* pathogens (*e.g.,* Lipp *et al.,* 2002). For example, increasing prevalence and diversity of *Vibrio* species has been noted in northern Atlantic waters of the United States coincident with warm water (Thompson *et al.,* 2004). Additionally, although most cases of *V. vulnificus* infection are attributed to Gulf Coast states, this species recently has been isolated from northern waters in the United States (Pfeffer *et al.,* 2003; Randa *et al.,* 2004).

The most striking example of an increased range in pathogen distribution and incidence was documented in 2004, when an outbreak of shellfish-associated *V. parahaemolyticus* was reported from Prince William Sound in Alaska (McLaughlin *et al.,* 2005). *V. parahaemolyticus* had never been isolated from Alaskan shellfish before and it was thought that Alaskan waters were too cold to support the species (McLaughlin *et al.,* 2005). In the period preceding the July 2004 outbreak, water temperatures in the harvesting area consistently exceeded 15^{o} C and the mean daily water temperatures were significantly higher than in the prior six years (McLaughlin *et al.,* 2005). This outbreak extended the northern range of oysters known to contain *V. parahaemolyticus* and cause illness by 1,000 km. Given the well-documented association between increasing sea surface temperatures and proliferation of many *Vibrio* species, evidence suggests that increasing global temperatures will lead to an increased burden of disease associated with certain *Vibrio* species in the United States, especially *V. vulnificus* and *V. parahaemolyticus*.

Protozoan parasites, particularly *Cryptosporidium* and *Giardia*, contribute significantly to waterborne and to a lesser extent foodborne disease burdens in the United States. Both parasites are zoonotic and form environmentally resistant infective stages, with only 10-12 oocysts or cysts required to cause disease. In 1998, 1.2 cases of cryptosporidiosis per 100,000 people were reported in the United States (Dietz and Roberts, 2000); the immunocompromised are at particularly high risk (Casman *et al.,* 2001; King and Monis, 2006). Between 2003 and 2004, of the 30 reported outbreaks of gastroenteritis from recreational water, 78.6% were due to *Cryptosporidium* and 14.3% were due to *Giardia* (Dzuiban *et al.*, 2006). *Giardia* has historically been the most commonly diagnosed parasite in the United States; between 1992 and 1997 there were 9.5 cases per 100,000 people (Furness *et al.*, 2000). Both *Cryptosporidium* and *Giardia* case reports peak in late summer and early fall, particularly among younger age groups (Dietz and Roberts, 2000; Furness *et al.*, 2000). For both parasites, peak rates of reported infection in Massachusetts occurred approximately one month after the annual temperature peak (Naumova *et al.*, 2006). The lagged association between peak annual temperatures and peaks in reported cases in late summer has been attributed to increased exposure during the summer bathing season, especially in the younger age groups, and to a slight lag in reporting (Dietz and Roberts, 2000; Furness *et al.*, 2000; Casman *et al.*, 2001). With increasing global temperatures, an increase in recreational use of water can be reasonably expected and could lead to increased exposure among certain groups, especially children.

Naegleria fowleri is a free-living amboeboflagellate found in lakes and ponds at warm temperatures, either naturally or in thermally polluted bodies of water. While relatively rare, infections are almost always fatal (Lee *et al.*, 2002). *N. fowleri* can be detected in environmental waters at rates up to 50% (Wellings *et al.*, 1977) at water temperatures above 25^{o}C (Cabanes *et al.*, 2001). Cases are consistently reported in the United States; between 1999 and 2000, four cases (all fatal) were reported. While *N. fowleri* continues to be a rare disease, it remains more common in the United States than elsewhere in the world (Marciano-Cabral *et al.*, 2003). Given its association with warm water, elevated temperatures could increase this pathogen’s range.

Epidemiologically significant viruses for food and water exposure include enteroviruses, rotaviruses, hepatitis A virus, and norovirus. Viruses account for 67% of foodborne disease, and the vast majority of these are due to norovirus (Mead *et al.*, 1999). Rotavirus accounts for a much smaller fraction of viral foodborne disease (Mead *et al.*, 1999), but is a significant cause of diarrheal disease among infants and young children (Charles *et al.*, 2006). Enteroviruses are not reportable and therefore incidence rates are poorly reflected in surveillance summaries (Khetsuriani *et al.*, 2006). With the exception of hepatitis A (Naumova *et al.*, 2006), enteric viral infection patterns follow consistent year to year trends. Enteroviruses are characterized by peaks in cases in the early to late summer (Khetsuriani *et al.*, 2006), while rotavirus and norovirus infections typically peak in the winter (Cook *et al.*, 1990; Lynch *et al.*, 2006). No studies have been able to identify a clear role for temperature in viral infection patterns.

An analysis of waterborne outbreaks associated with drinking water in the United States between 1948 and 1994 found that 51% of outbreaks occurred following a daily precipitation event in the 90th percentile and 68% occurred when precipitation levels reached the 80th percentile (Curriero *et al.*, 2001) (Figure 2.4). Similarly, Thomas *et al.*, (2006) found that the risk of waterborne disease doubled when rainfall amounts surpassed the 93rd percentile. Rose *et al.*, (2000) found that the relationship between rainfall and disease was stronger for surface water outbreaks, but the association was significant for both surface and groundwater sources. In 2000, groundwater used for drinking water in

Walkerton, Ontario was contaminated with *E. coli* O157:H7 and *Campylobacter* during rains that surpassed the 60-year event mark for the region and the 100-year event mark in local areas (Auld *et al.,* 2004). In combination with preceding record high temperatures, 2,300 people in a community of 4,800 residents became ill (Hrudey *et al.,* 2003; Auld *et al.,* 2004).

Figure 2.4 Drinking Waterborne Disease Outbreaks and 90%-ile Precipitation Events (a two month lag precedes outbreaks); 1948 – 1994.

Floodwaters may increase the likelihood of contaminated drinking water and lead to incidental exposure to standing floodwaters. In 1999, Hurricane Floyd hit North Carolina and resulted in severe flooding of much of the eastern portion of the state, including extensive hog farming operations. Residents in the affected areas experienced over twice the rate of gastrointestinal illness following the flood (Setzer and Domino, 2004). Following the severe floods of 2001 in the Midwest, contact with floodwater was shown to increase the rate and risk of gastrointestinal illness, especially among children (Wade *et al.,* 2004); however, consumption of tap water was not a risk factor as drinking water continued to meet all regulatory standards (Wade *et al.,* 2004).

2.2.4.3 Influenza

Influenza may be considered a zoonosis in that pigs, ducks, etc. serve as non-human hosts to the influenza viruses (*e.g.,* H3N2, H1N1) that normally infect humans (not H5N1). A number of recent studies evaluated the influence of weather and climate variability on the timing and intensity of the annual influenza season in the United States and Europe. Results indicated that cold winters alone do not predict pneumonia and influenza (P&I)-related winter deaths, even though cold spells may serve as a short-term trigger (Dushoff *et al.,* 2005), and that regional differences in P&I mortality burden may be attributed to climate patterns and to the dominant circulating virus subtype (Greene *et al.,* 2006). Studies in France and the United States demonstrated that the magnitude of seasonal transmission (whether measured as mortality or morbidity) during winter seasons is significantly higher during years with cold El Niño Southern Oscillation (ENSO) conditions than during warm ENSO years (Flahault *et al.,* 2004; Viboud *et al.,* 2004), whereas a study in California concluded that higher temperatures and El Niño years increased hospital admissions for viral pneumonia (Ebi *et al.,* 2001). In an attempt to better understand the spatio-temporal patterns of ENSO and influenza, Choi *et al.,* (2006) used stochastic models (mathematical models that take into account the presence of randomness) to analyze California county-specific influenza mortality, and produced maps that showed different risks during the warm and cool phases. In general, these studies of influenza further support the importance of climate drivers at a global and regional scale, but have not advanced our understanding of underlying mechanisms.

2.2.4.4 Valley Fever

Valley fever (Coccidioidomycosis) is an infectious disease caused by inhalation of the spores of a soil-inhabiting fungus that thrives during wet periods following droughts. The disease is of public health importance in the desert southwest. In the early 1990s, California experienced an epidemic of Valley Fever following five years of drought

(Kolivras and Comrie, 2003). Its incidence varies seasonally and annually, which may be partly due to climatic variations (Kolivras and Comrie, 2003; Zender and Talamantes, 2006). If so, then climate change could affect its incidence and geographic range.

2.2.4.5 Morbidity and Mortality Due to Changes in Air Quality

Millions of Americans continue to live in areas that do not meet the health-based National Ambient Air Quality Standards (NAAQS) for ozone and fine particulate matter (PM2.5). Both ozone and PM2.5 have well-documented health effects, and levels of these two pollutants have the potential to be influenced by climate change in a variety of ways.

Ground-level ozone is formed mainly by reactions that occur in polluted air in the presence of sunlight. Nitrogen oxides (emitted mainly by burning of fuels) and volatile organic compounds (emitted both by burning of fuels and by evaporation from vegetation and stored fuels, solvents, and other chemicals) are the key precursor pollutants for ozone formation. Ozone formation increases with greater sunlight and higher temperatures; it reaches peak concentrations during the warm half of the year, and then mostly in the late afternoon and early evening. Cloud cover and mixing height are two additional meteorological factors that influence ozone concentrations. It has been firmly established that breathing ozone results in short-term, reversible decreases in lung function (Folinsbee *et al.*, 1988) as well as inflammation deep in the lungs (Devlin *et al.*, 1991). In addition, epidemiology studies of people living in polluted areas have suggested that ozone may increase the risk of asthma-related hospital visits (Schwartz, 1995), premature mortality (Kinney and Ozkaynak, 1991; Bell *et al.*, 2004), and possibly the development of asthma (McConnell *et al.*, 2002). Vulnerability to ozone health effects is greater for persons who spend time outdoors during episode periods, especially with physical exertion, because this results in a higher cumulative dose to the lung. Thus, children, outdoor laborers, and athletes may be at greater risk than people who spend more time indoors and who are less active. At a given lung dose, little has been firmly established about vulnerability as a function of age, race, and/or existing health status. However, because their lungs are inflamed, asthmatics are potentially more vulnerable than non-asthmatics.

PM2.5 is a far more complex pollutant than ozone, consisting of all airborne solid or liquid particles that share the property of being less than 2.5 micrometers in aerodynamic diameter.2 All such particles are included, regardless of their size, composition, and biological reactivity. PM2.5 has complex origins, including primary particles directly emitted from sources and secondary particles that form via atmospheric reactions of precursor gases. Most of the particles captured as PM2.5 arise from burning of fuels, including primary particles such as diesel soot and secondary particles such as sulfates and nitrates. Epidemiologic studies have demonstrated associations between both short-term and long-term average ambient concentrations and a variety of adverse health outcomes including respiratory symptoms such as coughing and difficulty breathing,

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[2] Aerodynamic diameter is defined in a complex way to adjust for variations in shape and density of various particles, and is based on the physical diameter of a water droplet that would settle to the ground at the same rate as the particle in question. For a spherical water particle, the aerodynamic and physical diameters are identical.

decreased lung function, aggravated asthma, development of chronic bronchitis, heart attack, and arrhythmias (Dockery *et al.,* 1993; Samet *et al.,* 2000; Pope *et al.,* 1995, 2002, 2004; Pope and Dockery, 2006; Dominici et al, 2006; Laden *et al.,* 2006). Associations have also been reported for increased school absences, hospital admissions, emergency room visits, and premature mortality. Susceptible individuals include people with existing heart and lung disease, and diabetics, children, and older adults. Because the mortality risks of PM2.5 appear to be mediated through narrowing of arteries and resultant heart impacts (Künzli *et al.,* 2005), persons or populations with high blood pressure and/or pre-existing heart conditions may be at increased risk. In a study of mortality in relation to long-term PM2.5 concentrations in 50 U.S. cities, individuals without a high school education demonstrated higher concentration/response functions that those with more education (Pope *et al.,* 2002). This result suggests that low education was a proxy for increased likelihood of engaging in outdoor labor with an associated increase in exposure to ambient air.

Using a coupled climate-air pollution three-dimensional model, Jacobson (2008) compared the health effects of pre-industrial vs. present day atmospheric concentrations of CO_2. The results suggest that increasing concentrations of CO_2 increased tropospheric ozone and PM2.5, which increased mortality by about 1.1% per degree temperature increase over the baseline rate; Jacobson estimated that about 40% of the increase was due to ozone and the rest to particulate matter. The estimated mortality increase was higher in locations with poorer air quality.

2.2.4.6 Aeroallergens and Allergenic Diseases

Climate change has caused an earlier onset of the spring pollen season for several species in North America (Casassa *et al.,* 2007). Although data are limited, it is reasonable to infer that allergenic diseases caused by pollen, such as allergic rhinitis, also have experienced concomitant changes in seasonality (Emberlin *et al.,* 2002; Burr *et al.,* 2003). Several laboratory studies suggest that increasing CO_2 concentrations and temperatures could increase ragweed pollen production and prolong the ragweed pollen season (Wan *et al.,* 2002; Wayne *et al.,* 2002; Singer *et al.,* 2005; Ziska *et al.,* 2005; Rogers *et al.,* 2006) and increase some plant metabolites that can affect human health (Ziska *et al.,* 2005; Mohan *et al.,* 2006). Although there are suggestions that the abundance of a few species of airborne pollens has increased due to climate change, it is unclear whether the allergenic content of these pollen types has changed (Huynen and Menne, 2003; Beggs and Bambrick, 2005). The introduction of new invasive species associated with climatic and other changes, such as ragweed and poison ivy, may increase current health risks. There are no projections of the possible impacts of climate change on allergenic diseases.

2.3 Projected Health Impacts of Climate Change in the United States

2.3.1 Heat-Related Mortality

Determinants of how climate change could alter heat-related mortality include actual changes in the mean and variance of future temperatures; factors affecting temperature variability at the local scale; demographic and health characteristics of the population; and policies that affect the social and economic structure of communities, including urban design, energy policy, water use, and transportation planning. Barring an unexpected and catastrophic economic decline, residential and industrial development will increase over the coming decades, which could increase urban heat islands in the absence of urban design and new technologies to reduce heat loads.

The U.S. population is aging; the percent of the population over age 65 is projected to be 13% by 2010 and 20% by 2030 (over 50 million people) (Day, 1996). Older adults are physiologically and socially vulnerable (Khosla and Guntupalli, 1999; Klinenberg, 2002) to hot weather and heatwaves, suggesting that heat-related mortality could increase. Evidence that diabetics are at greater risk of heat-related mortality (Schwartz 2005), along with the increasing prevalence of obesity and diabetes (Seidell, 2000; Visscher and Seidell, 2001), suggests that reduced fitness and higher-fat body composition may contribute to increased mortality.

Table 2.1 summarizes projections of temperature-related mortality either in the United States or in temperate countries whose experience is relevant to the United States (Dessai, 2003) (Woodruff *et al.*, 2005) (Knowlton *et al.*, 2007) (CLIMB, 2004; Hayhoe *et al.*, 2004). Similar studies are underway in Europe (Kosatsky *et al.*, 2006; Lachowsky and Kovats, 2006). All studies used downscaled projections of future temperature distributions in the geographic region of interest. The studies used different approaches to incorporate likely future adaptation, addressing such issues as increased availability of air conditioning, heatwave early warning systems, demographic changes, and enhanced services such as cooling shelters and physiological adaptation.

Time-series studies also can shed light on potential future mortality during temperature extremes. Heat-related mortality has declined over the past decades (Davis *et al.*, 2002; Davis *et al.*, 2003a; Davis *et al.*, 2003b). A similar trend, for cold and heat-related mortality, was observed in London over the last century (Carson *et al.*, 2006). The authors speculate that these declines are due to increasing prevalence of air-conditioning (in the United States), improved health care, and other factors. These results do not necessarily mean that future increases in heat-related mortality may not occur in the United States, as some have claimed (Davis *et al.*, 2004), because the percentage of the population with access to air conditioning is high in most regions (thus with limited possibilities for increasing access). Further, population level declines may obscure persistent mortality impacts in vulnerable groups.

In summary, given the projections of increases in the frequency, intensity, and duration of heatwaves and projected demographic changes, the at-risk population will increase (highly likely). The extent to which mortality increases will depend on the effective implementation of a range of adaptation options, including heatwave early warning systems, urban design to reduce heat loads, and enhanced services during heatwaves.

2.3.2 Hurricanes, Floods, Wildfires and Health Impacts

No studies have projected the future health burdens of extreme weather events. There is concern that climate change could increase the frequency and/or severity of extreme events, including hurricanes, floods, and wildfires.

Theoretically, climate change could increase the frequency and severity of hurricanes by warming tropical seas where hurricanes first emerge and gain most of their energy (Pielke *et al.,* 2005; Trenberth, 2005; Halverson, 2006). Controversy over whether hurricane intensity increased over recent decades stem less from the conceptual arguments than from the limitations of available hurricane incidence data (Halverson, 2006; Landsea, 2005; Pielke *et al.,* 2005; Trenberth, 2005). Even if climate change increases the frequency and severity of hurricanes, it will be difficult to definitively identify this trend for some time because of the relatively short and highly variable historical data available as a baseline for comparison. Adding to the uncertainty, some research has projected that climate change could produce future conditions that might hinder the development of Atlantic hurricanes despite the warming of tropical seas (NOAA, 2007c).

Evidence suggests that the intensity of Atlantic hurricanes and tropical storms has increased over the past few decades. SAP3.3 indicates that there is evidence for a human contribution to increased sea surface temperatures in the tropical Atlantic and there is a strong correlation to Atlantic tropical storm frequency, duration, and intensity. However, a confident assessment will require further studies. An increase in extreme wave heights in the Atlantic since the 1970s has been observed: consistent with more frequent and intense hurricanes (CCSP, 2008).

For North Atlantic hurricanes, SAP3.3 concludes that it is likely that wind speeds and core rainfall rates will increase (Henderson-Sellers *et al.,* 1998; Knutson and Tuleya, 2004, 2008; Emanuel, 2005). However, SAP3.3 concluded that “frequency changes are currently too uncertain for confident projection” (CCSP, 2008). SAP3.3 also found that the spatial distribution of hurricanes will likely change. Storm surge is likely to increase due to projected sea level rise, though the degree to which these will increase has not been adequately studied (CCSP, 2008).

Theoretical arguments for increases in extreme precipitation and flooding are based on the principles of the hydrological cycle where increasing average temperature will intensify evaporation and subsequently increase precipitation (Bronstert, 2003; Kunkel, 2003, Senior *et al.,* 2002). Looking at the available data for evidence of a climate change signal, evidence suggests that the number of extreme precipitation events in the United States has increased (Balling Jr. and Cerveny, 2003; Groisman *et al.,* 2004; Kunkel, 2003). However, these results are not as consistent when evaluated by season or region (Groisman *et al.,* 2004).

Projections of changes in the future incidence of extreme-precipitation and flooding rely on the results from general circulation models (GCMs). These models project increases in mean precipitation with a disproportionate increase in the frequency of extreme precipitation events (Senior *et al.*, 2002). Kim (2003) used a regional climate model to project that a doubling in CO_2 concentrations in roughly 70 years could increase the number of days with at least 0.5 mm of precipitation by roughly 33% across the study's defined elevation gradients in the western United States. Furthermore, the IPCC concluded that it is very likely (>90% certainty) that trends in extreme precipitation will continue in the 21st century (IPCC, 2007a).

Studies modeling future wildfire incidence in the western United States using GCM outputs project increasingly severe wildfires, measured both in terms of energy released and the number of fires that avoid initial containment in areas that GCMs project will be increasingly dry (Brown *et al.*, 2004; Fried *et al.*, 2004). In general, these results suggest much of the western United States could face an increasing wildfire risk from climate change. The apparent exception could be the Pacific Northwest, including northern California, where GCMs generally project a wetter future.

Factors independent of the impacts of and responses to climate change will affect vulnerability to extreme events, including population growth, continued urban sprawl, population shifts to coastal areas, and differences in the degree of community preparation for extreme events (U.S. Census Bureau, 2004).

All else equal, the anticipated demographic changes will increase the size of the U.S. population at risk for future extreme weather events (very likely). This raises the potential for increasing total numbers of adverse health impacts from these events, even if the rate these impacts are experienced decreases (where the rate reflects the number of impacts per some standard population size among those actually experiencing the events).

2.3.3 Vectorborne and Zoonotic Diseases

Modeling the possible impacts of climate change on VBZ diseases is complex, and few studies have made projections for diseases of concern in the United States. Studies suggest that temperature influences the distributions of Ixodes spp. ticks that transmit pathogens causing Lyme disease in the United States (Brownstein *et al.*, 2003) and Canada (Ogden *et al.*, 2006), and tick-borne encephalitis in Sweden (Lindgren *et al.*, 2000). Higher minimum temperatures were generally favorable to the potential of expanding tick distributions and greater local abundance of these vectors. However, changing patterns of tick-borne encephalitis (TBE) in Europe are not consistently related to changing climate (Randolph, 2004a). Climate change is projected to decrease the geographic range of TBE in areas of lower latitude and elevation as transmission expands northward (Randolph and Rogers, 2000).

2.3.4 Water- and Foodborne Diseases

Several important pathogens that are commonly transmitted by food or water may be susceptible to changes in replication, survival, persistence, habitat range, and transmission under changing climatic and environmental conditions (Table 2.2). Many of these agents show seasonal infection patterns (indicating potential underlying environmental or weather control), are capable of survival or growth in the environment, or are capable of waterborne transport. Factors that may affect these pathogens include changes in temperature, precipitation, extreme weather events (*i.e.*, storms), and ecological shifts. While the US has successful programs to protect water quality under the Safe Drinking Water Act and the Clean Water Act, some contamination pathways and routes of exposure do not fall under regulatory programs (e.g., dermal absorption from floodwaters, swimming in lakes and ponds with elevated pathogen levels, etc.).

2.3.5 Air Quality Morbidity and Mortality

The sources and conditions that give rise to elevated ozone and PM2.5 in outdoor air in the United States have been and will continue to be affected by global environmental changes related to land use, economic development, and climate change. Conversions of farmland and forests into housing developments and the infrastructure of schools and businesses that support them change the spatial patterns and absolute amounts of emissions from fuel combustion related to transportation, space heating, energy production, and other activities. Resulting vegetation patterns affect biogenic volatile organic compound (VOC) emissions that influence ozone production. Conversion of land from natural to man-made also changes the degree to which surfaces absorb solar energy (mostly in the form of light) and later re-radiate that energy as heat, which contributes to urban heat islands. In addition to their potential for increasing heat-related health effects, heat islands also can influence local production and dispersion of air pollutants like ozone and PM2.5.

It is important to recognize that U.S. Environmental Protection Agency administers a well-developed and successful national regulatory program for ozone, PM2.5, and other criteria pollutants. Although many areas of the US remain out of compliance with the ozone and PM2.5 standards, there is evidence for gradual improvements in recent years, and this progress can be expected to continue with more stringent emissions controls going forward in time. Thus, the influence of climate change on air quality will play out against a backdrop of ongoing regulatory control of both ozone and PM2.5 that will shift the baseline concentrations of these two important air pollutants. On the other hand, most of the studies that have examined potential future climate impacts on air quality reviewed below have tried to isolate the climate effect by holding precursor emissions constant over future decades. Thus, the focus has been on examining the sensitivity of ozone concentrations to alternative future climates rather than on attempting to predict actual future ozone concentrations.

The influence of meteorology on air quality is substantial and well-established (EPRI, 2005), raising the possibility that changes in climate could alter patterns of air pollution concentrations. Temperature and cloud cover affect the chemical reactions that lead to ozone and secondary particle formation. Winds, vertical mixing, and rainfall patterns influence the movement and dispersion of anthropogenic pollutant emissions in the atmosphere, with generally improved air quality at higher winds, mixing heights, and rainfall. The most severe U.S. air pollution episodes occur with atmospheric conditions that limit both vertical and horizontal dispersion over multi-day periods. Methods used to study the influence of climatic factors on air quality range from statistical analyses of empirical relationships to integrated modeling of future air quality resulting from climate change. To date, most studies have been limited to climatic effects on ozone. Additional research is needed on the impacts of climate change on anthropogenic particulate matter concentrations.

Leung and Gustafson (2005) used regional climate simulations for temperature, solar radiation, precipitation, and stagnation/ventilation, and projected worse air quality in Texas and better air quality in the Midwest in 2045-2055 compared with 1995-2005. Aw and Kleeman (2003) simulated an episode of high air pollution in southern California in 1996 with observed meteorology and then with higher temperatures. Ozone concentrations increased up to 16% with higher temperatures, while the PM2.5 response was more variable due to opposing forces of increased secondary particle formation and more evaporative losses from nitrate particles. Bell and Ellis (2004) showed greater sensitivity of ozone concentrations in the Mid-Atlantic to changes in biogenic than to changes in anthropogenic emissions. Ozone's sensitivity to changing temperatures, absolute humidity, biogenic VOC emissions, and pollution boundary conditions on a fine-scale (4 km grid resolution) varied in different regions of California (Steiner *et al.,* 2006).

Several studies explored the impacts of climate change alone on future ozone projections. In a coarse-scale analysis of pollution over the continental United States, Mickley *et al.,* (2004) used the GISS (NASA Goddard Institute for Space Studies) 4x5º model to project that, due to climate change alone (A1b emission scenario), air pollution could increase in the upper Midwest due to decreases between 2000 and 2052 in the frequency of Canadian frontal passages that clear away stagnating air pollution episodes. The 2.8x2.8º Mozart global chemistry/climate model was used to explore global background and urban ozone changes over the 21st century in response to climate change, with ozone precursor emissions kept constant at 1990s levels (Murazaki and Hess, 2006). While global background decreased slightly, the urban concentrations due to U.S. emissions increased.

As part of the New York Climate and Health Study, Hogrefe and colleagues conducted local-scale analyses of air pollution impacts of future climate changes using integrated modeling (Hogrefe *et al.,* 2004a,b,c; 2005a,b) to examine the impacts of climate and land use changes on heat- and ozone-related health impacts in the NYC metropolitan area (Knowlton *et al.,* 2004; Kinney *et al.,* 2006; Bell *et al.,* 2007; Civerolo *et al.*, 2006). The GISS 4x5º was used to simulate hourly meteorological data from the 1990s through the 2080s based on the A2 and B2 SRES scenarios. The A2 scenario assumes roughly double the CO2 emissions of B2. The global climate outputs were downscaled to a 36 km grid over the eastern United States using the MM5 regional climate model. The MM5 results were used in turn as inputs to the CMAQ regional-scale air quality model. Five summers (June, July, and August) in each of four decades (1990s, 2020s, 2050s, and 2080s) were simulated at the 36 km scale. Pollution precursor emissions over the eastern United States were based on U.S. EPA estimates at the county level for 1996. Compared with observations from ozone monitoring stations, initial projections were consistent with ozone spatial and temporal patterns over the eastern United States in the 1990s (Hogrefe *et al.,* 2004a). Average daily maximum 8-hour concentrations were projected to increase by 2.7, 4.2, and 5.0 ppb in the 2020s, 2050s, and 2080s, respectively due to climate change (Figure 2.5) (Hogrefe *et al.*, 2004b). The influence of climate on mean ozone values was similar in magnitude to the influence of rising global background by the 2050s, but climate had a much greater impact on extreme values than did the global background. When biogenic VOC emissions were allowed to increase in response to warming, an additional increase in ozone concentrations was projected that was similar in magnitude to that of climate alone (Hogrefe *et al.*, 2004b). Climate change shifted the distribution of ozone concentrations towards higher values, with larger relative increases in future decades (Figure 6).

Figure 2.5 (a) Summertime Average Daily Maximum 8-hour Ozone Concentrations (ppb) for the 1990s and Changes for the (b) 2020s relative to the 1990s, (c) 2050s relative to the 1990s, and (d) 2080s relative to the 1990s. All are based on the A2 Scenario relative to the 1990s. Five consecutive summer seasons were simulated in each decade.

Figure 2.6 Frequency Distributions of Summertime Daily Maximum 8-hr Ozone Concentrations over the eastern United States in the 1990s, 2020s, and 2050s based on the A2 Scenario.

Projections in Germany also found larger climate impacts on extreme ozone values (Forkel and Knoche, 2006). Using the IS92a business-as-usual scenario, the ECHAM4 GCM projected changes for the 2030s compared with the 1990s; the output was downscaled to a 20 km grid using a modification of the MM5 regional model, which was in-turn linked to the RADM2 ozone chemistry model. Both biogenic VOC emissions and soil NO emissions were projected to increase as temperatures rose. Daily maximum ozone concentrations increased by between 2 and 6 ppb (6-10%) across the study region. The number of cases where daily maximum ozone exceeded 90 ppb increased by nearly four-fold, from 99 to 384.

Using the NYCHP integrated model, PM2.5 concentrations are projected to increase with climate change, with the effects differing by component species, with sulfates and primary PM increasing markedly and with organic and nitrated components decreasing, mainly due to movement of these volatile species from the particulate to the gaseous phase (Hogrefe *et al.*, 2005b; 2006).

Hogrefe *et al.*, (2005b) noted that “the simulated changes in pollutant concentrations stemming from climate change are the result of a complex interaction between changes in transport, mixing, and chemistry that cannot be parameterized by spatially uniform linear regression relationships.” Additional uncertainties include how population vulnerability, mix of pollutants, housing characteristics, and activity patterns may differ in the future. For example, in a warmer world, more people may stay indoors with air conditioners in the summer when ozone levels are highest, decreasing personal exposures (albeit with potential increases in pollution emissions from power plants). Baseline mortality rates may change due to medical advances, changes in other risk factors such as smoking and diet, and aging of the population.

The New York Climate and Health Project examined the marginal sensitivity of health to changes in climate to project the potential health impacts of ozone in the eastern United States (Knowlton *et al.*, 2004; Bell *et al.*, 2007). Knowlton and colleagues computed absolute and percentage increases in ozone-related daily summer-season deaths in the NYC metropolitan region in the 2050s as compared with the 1990s using a downscaled GCM/RCM/air quality model (Knowlton *et al.*, 2004; Kinney *et al.*, 2006). The availability of county-scale ozone projections made it possible to compare impacts in the urban core with those in outlying areas. Increases in ozone-related mortality due to climate change ranged from 0.4 to 7.0% across 31 counties. Bell and colleagues expanded the analysis to 50 eastern cities and examined both mortality and hospital admissions (Bell *et al.*, 2007). Average ozone concentrations were projected to increase by 4.4 ppb (7.4%) in the 2050s; the range was 0.8% to 13.7%. In addition, ozone red alert days could increase by 68%. Changes in health impacts were of corresponding magnitude.

Based on the new research findings published since the previous assessment, the following summary statements can be made:

- There is an established but incomplete level of knowledge suggesting that both ozone and fine particle concentrations may be affected by climate change.
- A substantial body of new evidence on ozone supports the interpretation that ozone concentrations would be more likely to increase than decrease in the United States as a result of climate change, holding precursor emissions constant.
- Too few data yet exist for PM to draw firm conclusions about the direction or magnitude of climate impacts

2.4 Vulnerable Regions and Subpopulations

In adapting the IPCC's definitions[3] to public health, "vulnerability" can be defined as the summation of all risk and protective factors that ultimately determine whether an individual or subpopulation experiences adverse health outcomes, and "sensitivity" can be defined as an individual's or subpopulation's increased responsiveness, primarily for biological reasons, to a given exposure. Thus, specific subpopulations may experience heightened vulnerability for climate-related health effects for a wide variety of reasons. Biological sensitivity may be related to the developmental stage, presence of pre-existing chronic medical conditions (such as the sensitivity of people with chronic heart conditions to heat-related illness), acquired factors (such as immunity), and genetic factors (such as metabolic enzyme subtypes that play a role in sensitivity to air pollution effects). Socioeconomic factors also play a critical role in altering vulnerability and sensitivity to environmentally-mediated factors. They may alter the likelihood of exposure to harmful agents, interact with biological factors that mediate risk (such as nutritional status), and/or lead to differences in the ability to adapt or respond to exposures or early phases of illness and injury. For public health planning, it is critical to

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[3] IPCC Second Assessment. Climate Change 1995. Available at http://www.ipcc.ch/pub/sa(E).pdf. Accessed 11-12-07.

recognize populations that may experience synergistic effects of multiple risk factors for health problems related to climate change and to other temporal trends.

2.4.1 Vulnerable Regions

Populations living in certain regions of the United States may experience altered risks for specific climate-sensitive health outcomes due to their regions' baseline climate, abundance of natural resources such as fertile soil and fresh water supplies, elevation, dependence on private wells for drinking water, or vulnerability to coastal surges or riverine flooding. Some regions' populations may in fact experience multiple climate-sensitive health problems simultaneously. One approach to identifying such areas is to map regions currently experiencing increased rates of climate-sensitive health outcomes or other indicators of increased climate risk, as illustrated in Figure 2.7a-2.7d.

Residents of low-lying coastal regions, which are common locations for hurricane landfalls and flooding, are particularly vulnerable to the health impacts of climate change. Those who live in the Gulf Coast region, for example, are likely to experience increased human health burdens due to the constellation of more intense storms, greater sea level rise, coastal erosion, and damage to freshwater resources and infrastructure. Other coastal areas may also experience the combination of sea level rise chronically threatening water supplies and periodic infrastructure damage from more intense storms. Populations in the Southwest and Great Lakes regions may experience increased strain on water resources and availability due to climate change. More intense heat waves and heat-related illnesses may take place in regions where extreme heat events already occur, such as interior continental zones of the United States. High-density urban populations will experience heightened health risks, in part due to the heat-island effect. In addition, increased demand for electricity during summers may lead to greater air pollution levels (IPCC, 2007b).

Figure 2.7 a-d U.S. maps indicating counties with existing vulnerability to climate sensitive health outcomes: (a) location of hurricane landfalls; (b) extreme heat events, defined by CDC as temperatures 10 or more degrees above the average high temperature for the region and lasting for several weeks; (c) percentage of population over age 65; (d) West Nile Virus cases reported in 2004. Historical disease activity, especially in the case of WNV, is not necessarily predictive of future vulnerability.

2.4.2 Specific Subpopulations at Risk

Vulnerable subpopulations may be categorized according to specific health endpoints. (Table 2.3). While this is typically the way the scientific literature reports risk factors for adverse health effects, this section discusses vulnerability for a variety of climate-sensitive health endpoints one subpopulation at a time.

2.4.2.1 Children

Children's small body mass to surface area ratio and other factors make them more vulnerable to heat-related morbidity and mortality (AAP, 2000), while their increased breathing rates relative to body size, time spent outdoors, and developing respiratory tracts heighten their sensitivity to harm from ozone air pollution (AAP, 2004). In

addition, children's relatively naïve immune systems increase the risk of serious consequences from water and foodborne diseases; specific developmental factors make them more vulnerable to complications from specific severe infections like *E Coli* O157:H7.
Children's lack of immunity also plays a role in higher risk of mortality from malaria (CDC, 2004b). Conversely, maternal antibodies to dengue in infants convey increased risk of developing dengue hemorrhagic syndromes. A second peak of greater risk of complications from dengue appears in children between the ages of 3 and 5 (Guzman and Khouri, 2002).

Children may also be more vulnerable to psychological complications of extreme weather events related to climate change. Following two floods in Europe in the 1990s, children demonstrated moderate to severe stress symptoms (Becht *et al.*, 1998; cited in Hajat *et al.,* 2003) and long-term PTSD, depression, and dissatisfaction with ongoing life (Bokszanin, 2000; cited in Hajat *et al.*, 2003).

2.4.2.2 Older Adults

Health effects associated with climate change pose significant risks for the elderly, who often have frail health and limited mobility. Older adults are more sensitive to temperature extremes, particularly heat (Semenza *et al.,* 1996; Medina-Ramon *et al.,* 2006); individuals 65 years of age and older comprised 72% of the heat-related deaths in the 1995 Chicago heatwave (Whitman *et al.,* 1997). The elderly are also more likely to have preexisting medical conditions, including cardiovascular and respiratory illnesses, which may put them at greater risk of exacerbated illness by climate-related events or conditions. For example, a 2004 rapid needs assessment of older adults in Florida found that Hurricane Charley exacerbated preexisting, physician-diagnosed medical conditions in 24-32% of elderly households (CDC, 2004a). Also, effects of ambient particulate matter on daily mortality tend to be greatest in older age groups (Schwartz, 1995).

2.4.2.3 Impoverished Populations

Even in the United States, the greatest health burdens related to climate change are likely to fall on those with the lowest socioeconomic status (O'Neill *et al.,* 2003a). Most affected are individuals with inadequate shelter or resources to find alternative shelter in the event their community is disrupted. While quantitative methods to assess the increase in risk related to these social and economic factors are not well-developed, qualitative insights can be gained by examining risk factors for mortality and morbidity from recent weather-related extreme events such as the 1995 heatwave in Chicago and Hurricane Katrina in 2005 (Box 2.1).

Studies of heatwaves identify poor housing conditions, including lack of access to air conditioning and living spaces with fewer rooms, as significant risk factors for heat-related mortality (Kalkstein, 1993; Semeza *et al.,* 1996). Higher heat-related mortality has been associated with socioeconomic indicators, such as lacking a high school education and living in poverty (Curriero *et al.,* 2002). Financial stress plays a role, as one study of the 1995 Chicago heatwave found that concern about the affordability of utility bills influenced individuals to limit air conditioning use (Klinenberg, 2002). The risk for exposure and sensitivity to air pollution is also elevated among groups in a lower socioeconomic position (O'Neill *et al.,* 2003a).

Air conditioning is an important short-term method for protecting health, but is not a sustainable long-term adaptation technology because the electricity use is often associated with greenhouse gas emissions and during heatwaves can overload the grid and contribute to outages (O'Neill, 2003c). Furthermore, the elderly with limited budgets and racial minorities are less likely to have access to air conditioning or to use it during hot weather (O'Neill *et al.,* 2005b, Sheridan, 2006). Incentives for and availability of high-efficiency, low energy-demand residential cooling systems, especially among disadvantaged populations, can advance health equity and minimize some of the negative aspects of air conditioning.

Another area of concern for impoverished populations is the impact that climate change may have on food systems and food supply. In the United States, food insecurity is a prevalent health risk among the poor, particularly poor children (Cook *et al.,* 2007). On a global scale, studies suggest that climate change is likely to contribute to food insecurity by reducing crop yield, most significantly at lower latitudes, due to shortened growing periods and decreases in water availability (Parry *et al.,* 2005). In the United States, changes in the price of food would likely contribute to food insecurity to a greater degree than overall scarcity.

The tragic loss of life that occurred after Hurricane Katrina underscores the increased vulnerability of special populations and demonstrates that, in the wake of extreme weather events, particularly those that disrupt medical infrastructure and require large-scale evacuation, treating individuals with chronic diseases is of critical concern (Ford *et al.,* 2006).

2.4.2.4 People with Chronic Conditions and Mobility and Cognitive Constraints

People with chronic medical conditions have an especially heightened vulnerability for the health impacts of climate change. Extreme heat poses a great risk for individuals with diabetes (Schwartz, 2005), and extreme cold has an increased effect on individuals with chronic obstructive pulmonary disease (Schwartz, 2005). People with mobility and cognitive constraints may be at particular risk during heatwaves and other extreme weather events (EPA, 2006). As noted above, those with chronic medical conditions are also at risk of worsened status as the result of climate-related stressors and limited access to medical care during extreme events.

2.4.2.5 Occupational Groups

Certain occupational groups, primarily by virtue of spending their working hours outdoors, are at greater risk of climate-related health outcomes. Outdoor workers in rural or suburban areas, such as electricity and pipeline utility workers, are at increased risk of infection with Lyme Disease, although evidence is lacking for greater risk of clinical illness (Schwartz and Goldstein, 1990; Piacentino and Schwartz, 2002). They and other outdoor workers have increased exposures to ozone air pollution and heat stress, especially if work tasks involve heavy exertion.

2.4.2.6 Recent Migrants and Immigrants

Residential mobility, migration, and immigration may increase vulnerability. For example, new residents in an area may not be acclimated to the weather patterns, have lower awareness of risks posed by local vectorborne diseases, and have fewer social networks to provide support during an extreme weather event. U.S. immigrants returning to their countries of origin to visit friends and relatives have also been shown to suffer increased risks of severe travel-associated diseases (Bacaner *et al.*, 2004, Angell and Cetron, 2005). This vulnerability may become more significant if such diseases, which include malaria, viral hepatitis, and typhoid fever, become more prevalent in immigrants' countries of origin because of climate change.

2.5 Adaptation

Realistically assessing the potential health effects of climate change must include consideration of the capacity to manage new and changing climatic conditions. Individuals, communities, governments, and other organizations currently engage in a wide range of actions to identify and prevent adverse health outcomes associated with weather and climate. Although these actions have been largely successful, recent extreme events and outbreaks of vectorborne diseases highlight areas for improvement (Confalonieri *et al.*, 2007). Climate change is likely to further challenge the ability of current programs and activities to control climate-sensitive health determinants and outcomes. Preventing additional morbidity and mortality requires consideration of all upstream drivers of adverse health outcomes, including developing and deploying adaptation policies and measures that consider the full range of health risks that are likely to arise with climate change.

In public health, prevention is the term analogous to adaptation, acknowledging that adaptation implies a set of continuous or evolving practices and not just upfront investments. Public health prevention is classified as primary, secondary, or tertiary. Primary prevention aims to prevent the onset of disease in an otherwise unaffected population (such as regulations to reduce harmful exposures to ozone). Secondary prevention entails preventive action in response to early evidence of health effects (including strengthening disease surveillance programs to provide early intelligence on the emergence or re-emergence of health risks at specific locations, and responding effectively to disease outbreaks, such as West Nile virus). Tertiary prevention consists of measures (often treatment) to reduce long-term impairment and disability and to minimize suffering caused by existing disease. In general, primary prevention is more effective and less expensive than secondary and tertiary prevention. For every health outcome, there are multiple possible primary, secondary, and tertiary preventions.

The degree to which programs and measures will need to be modified to address the additional pressures due to climate change will depend on factors such as the current burden of climate-sensitive health outcomes, the effectiveness of current interventions, projections of where, when, and how quickly the health burdens could change with changes in climate and climate variability (which depends on the rate and magnitude of climate change), the feasibility of implementing additional cost-effective interventions, other stressors that could increase or decrease resilience to impacts, and the social, economic, and political context within which interventions are implemented (Ebi *et al.*, 2006a). Failure to invest in adaptation may leave communities poorly prepared and increase the probability of severe adverse consequences (Haines *et al.*, 2006a,b).

Adaptation to climate change is basically a risk management issue. Adaptation and mitigation are the primary responses to manage current and projected risks. Mitigation and adaptation are not mutually exclusive; co-benefits to human health can result concurrently with implementation of mitigation and adaptation actions. A dialogue is needed on prioritizing the costs of mitigation actions designed to limit future climate change and the potential costs of continually trying to adapt to its impacts. This dialogue should explicitly recognize that there is no guarantee that future changes in climate will not present a threshold that poses technological or physical limits to which adaptation is not possible.

Adaptation policies and measures should address both projected risks and the regions and populations that currently are not well adapted to climate-related health risks. Because the degree and rate of climate change is projected to increase over time, adaptation will be a continual process of designing and implementing policies and programs to prevent adverse impacts from changing exposures and vulnerabilities (Ebi *et al.*, 2006). Clearly, the extent to which effective proactive adaptations are developed and deployed will be a key determinant of future morbidity and mortality attributable to climate change.

Regional vulnerabilities to the health impacts of climate change are influenced by physical, social, demographic, economic, and other factors. Adaptation activities take place within the context of slowly changing factors that are specific to a region or population, including specific population and regional vulnerabilities, social and cultural factors, the built and natural environment, the status of the public health infrastructure, and health and social services. Because these factors vary across geographic and temporal scales, adaptation policies and measures generally are more successful when focused on a specific population and location. Additional important factors include the degree of risk perceived, the human and financial resources available for adaptation, the available technological options, and the political will to undertake adaptation.

2.5.1 Actors and Their Roles and Responsibilities for Adaptation

Responsibility for the prevention of climate-sensitive health risks rests with individuals, community and state governments, national agencies, and others. The roles and responsibilities vary by health outcome. For example, individuals are responsible for taking appropriate action on days with declared poor air quality, with health care providers and others responsible for providing the relevant information, and government agencies providing the regulatory framework. Community governments play a central role in preparedness and response for extreme events because of their jurisdiction over police, fire, and emergency medical services. Early warning systems for extreme events such as heat waves (Box 2.2) and outbreaks of infectious diseases may be developed at the community or state level. The federal government funds research and development to increase the range of decision support planning and response tools. Medical and nursing schools are responsible for ensuring that health professionals are trained in the identification and treatment of climate-sensitive diseases. The Red Cross and other nongovernmental organizations (NGOs) often play critical roles in disaster response.

Additional research and development are needed to ensure that surveillance systems account for and anticipate the potential effects of climate change. Ensuring that surveillance systems account for and anticipate the potential effects of climate change will be beneficial. For example, surveillance systems in locations where changes in weather and climate may foster the spread of climate-sensitive pathogens and vectors into new regions would help advance our understanding of the associations between disease patterns and environmental variables. This knowledge could be used to develop early warning systems that warn of outbreaks before most cases have occurred. Increased understanding is needed of how to design these systems where there is limited knowledge of the interactions of climate, ecosystems, and infectious diseases (NAS, 2001).

There are no inventories in the United States of the various actors taking action to cope with climate change-related health impacts. However, the growing numbers of city and state actions on climate change show increasing awareness of the potential risks. As of 1 November 2007, more than 700 cities have signed the U.S. Mayors Climate Protection Agreement (http://www.seattle.gov/mayor/climate/cpaText.htm); although this agreement focuses on mitigation through increased energy efficiency, one strategy, planting trees, can both sequester CO_2 and reduce urban heat islands. The New England Governors and Eastern Canadian Premiers developed a Climate Change Action Plan because of concerns about public health associated with degradation in air quality, public health risks, the magnitude and frequency of extreme climatic phenomena and availability of water. (NEG/ECP, 2001). One action item focuses on the reduction and/or adaptation of negative social, economic, and environmental impacts. Activities being undertaken include a long-term phenology study, and studies on temperature increases and related potential impacts.

Strategies, policies, and measures implemented by community and state governments, federal agencies, NGOs, and other actors can change the context for adaptation by conducting research to assess vulnerability and to identify technological options available for adaptation, implementing programs and activities to reduce vulnerability, and shifting human and financial resources to address the health impacts of climate change. State and federal governments also can provide guidance for vulnerability assessments that consider a range of plausible future scenarios. The results of these assessments can be used to identify priority health risks (over time), particularly vulnerable populations and regions, effectiveness of current adaptation activities, and modifications to current activities or new activities to implement to address current and future climate change-related risks.

Table 2.4 summarizes the other roles and responsibilities of various actors for adapting to climate change. Note that viewing adaptation from a public health perspective results in similar activities being classified as primary rather than secondary prevention under different health outcomes. It is not possible to prevent the occurrence of a heatwave, so primary prevention focuses on actions such as developing and enforcing appropriate infrastructure standards, while secondary prevention focuses on implementing early warning systems and other activities. For vectorborne diseases, primary prevention refers to preventing exposure to infected vectors; in this case, early warning systems can be considered primary prevention. For most vectorborne diseases, there are few options for preventing disease onset once an individual has been bitten.

A key activity not included in this framework is research on the associations between weather / climate and various health outcomes, taking into consideration other drivers of those outcomes (*e.g.,* taking a systems-based approach), and projecting how those risks may change with changing weather patterns. Increased understanding of the human health risks posed by climate change is needed for the design of effective, efficient, and timely adaptation options.

2.5.2 Adaptation Measures to Manage Climate Change-Related Health Risks

Determining where populations are not effectively coping with current climate variability and extremes facilitates identification of the additional interventions that are needed now. However, given uncertainties in climate change projections, identifying current adaptation deficits is not sufficient to protect against projected health risks. Adaptation measures can be categorized into legislative policies, decision support tools, technology development, surveillance and monitoring of health data, infrastructure development, and other. Table 2.5 lists some adaptation measures for health impacts from heatwaves, extreme weather events, vectorborne diseases, waterborne diseases, and air quality. These measures are generic because the local context, including vulnerabilities and adaptive capacity, need to be considered in the design of programs and activities to be implemented.

An additional category of measures includes public education and outreach to provide information to the general public and specific vulnerable groups on climate risks to which they may be exposed and appropriate actions to take. Messages need to be specific to the region and group; for example, warnings to senior citizens of an impending heatwave should focus on keeping cool and drinking lots of water. Box 2.3 provides tips for dealing with extreme heatwaves developed by U.S. EPA with assistance from federal, state, local, and academic partners (U.S. EPA, 2006).

2.6 Conclusions

The conclusions from this assessment are consistent with those of the First National Assessment: climate change poses a risk for U.S. populations, with uncertainties limiting quantitative projections of the number of increased injuries, illnesses, and deaths attributable to climate change. However, the strength and consistency of projections for climatic changes for some exposures of concern to human health suggest that implementation of adaptation actions should commence now (Confalonieri *et al.,* 2007). Further, trends in factors that affect vulnerability, such as a larger and older U.S. population, will increase overall vulnerability to health risks. At the same time, the capacity of the U.S to implement effective and timely adaptation measures is assumed to remain high throughout this century, thus reducing the likelihood of severe health impacts if appropriate programs and activities are implemented. However, the nature of the risks posed by climate change means that some adverse health outcomes may not be avoidable, even with attempts at adaptation. Severe health impacts will not be evenly distributed across populations and regions, but will be concentrated in the most vulnerable groups.

Proactive policies and measures should be identified that improve the context for adaptation, reduce exposures related to climate variability and change, prevent the onset of climate-sensitive health outcomes, and increase treatment options. Future community, state, and national assessments of the health impacts of climate variability and change should identify gaps in adaptive capacity, including where barriers and constraints to implementation, such as governance mechanisms, need to be addressed.

Because of regional variability in the types of health stressors attributable to climate change and their associated responses, it is difficult to summarize adaptation at the national level. Planning for adaptation is hindered by the fact that downscaled climate projections, as well as other climate information and tools, are generally not available to local governments. Such data and tools are essential for sectors potentially affected by climate change to assess their vulnerability and possible adaptation options, catalogue, evaluate, and disseminate adaptation measures. Explicit consideration of climate change is needed in the many programs and research activities within federal, state, and local agencies that are relevant to adaptation to ensure that they have maximum effectiveness and timeliness in reducing future vulnerability. In addition, collaboration and coordination are needed across agencies and sectors to ensure protection of the American population to the current and projected impacts of climate change.

2.7 Expanding the Knowledge Base

Few research and data gaps have been filled since the First National Assessment. An important shift in perspective that occurred since the First National Assessment is a greater appreciation of the complex pathways and relationships through which weather and climate affect health, and the understanding that many social and behavioral factors will influence disease risks and patterns (NRC, 2001). Several research gaps identified in the First National Assessment have been partially filled by studies that address the differential effects of temperature extremes by community, demographic, and biological characteristics; that improve our understanding of exposure-response relationships for extreme heat; and that project the public health burden posed by climate-related changes in heatwaves and air quality. Despite these advances, the body of literature remains small, limiting quantitative projections of future impacts.

Improving our understanding of the linkages between climate change and health in the United States, may require a wide range of activities along the following lines:

- Improve characterization of exposure-response relationships, particularly at regional and local levels, including identifying thresholds and particularly vulnerable groups.
- Collect data on the early effects of changing weather patterns on climate-sensitive health outcomes.
- Collect and enhance long-term surveillance data on health issues of potential concern, including vectorborne and zoonotic diseases, air quality, pollen and mold counts, reporting of food- and waterborne diseases, morbidity due to temperature extremes, and mental health impacts from extreme weather events.
- Develop quantitative models of possible health impacts of climate change that can be used to explore the consequences of a range of socioeconomic and climate scenarios.
- Increase understanding of the processes of adaptation, including social and behavioral dimensions, as well as the costs and benefits of interventions.
- Evaluate the implementation of adaptation measures. For example, evaluation of heatwave warning systems, especially as they become implemented on a wider scale (NOAA, 2005), is needed to understand how to motivate appropriate behavior.
- Understand local and regional scale vulnerability and adaptive capacity to characterize the potential risks and the time horizon over which climate risks might arise; these assessments should include stakeholders to ensure their needs are identified and addressed in subsequent research and adaptation activities.
- Improve comprehensive estimates of the co-benefits of adaptation and mitigation policies in order to clarify trade-offs and synergies.
- Improve collaboration across the multiple agencies and organizations with responsibility and research related to climate change-related health impacts, such as weather forecasting, air and water quality regulations, vector control programs, and disaster preparation and response.
- Anticipate infrastructure requirements that will be needed to protect against extreme events such as heatwaves, and food- and waterborne diseases, or to alter urban design to decrease heat islands, and to maintain drinking and wastewater treatment standards and source water and watershed protection.
- Develop downscaled climate projections at the local and regional scale in order to conduct the types of vulnerability and adaptation assessments that will enable adequate response to climate change and to determine the potential for interactions between climate and other risk factors, including societal, environmental, and economic. The growing concern over impacts from extreme events demonstrates the importance of climate models that allow for stochastic generation of possible future events, to assess not only how disease and pathogen population dynamics might respond, but also to assess whether levels of preparedness are likely to be adequate.

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2.9 Boxes

Box 2.1 Vulnerable Populations and Hurricane Katrina

In 2005, Hurricane Katrina caused more than 1,500 deaths along the Gulf Coast, and many of these victims were members of vulnerable subpopulations, such as hospital and nursing-home patients, older adults who required care within their homes, and individuals with disabilities (U.S. CHSGA, 2006). The hurricane was complicated by a catastrophic failure of the levee system that was intended to shield those areas in New Orleans that lie at or below sea level. According to the Louisiana Department of Health and Hospitals, more than 45% of the state's identified victims were 75 years of age or older; 69% were above age 60 (LDHH, 2006). In Mississippi, 67% of the victims whose deaths were directly, indirectly, or possibly related to Katrina were 55 years of age or older (MSDH, 2005).

At hurricane evacuation centers in Louisiana, Mississippi, Arkansas, and Texas, chronic illness was the most commonly reported health problem, accounting for 33% or 4,786 of 14,531 visits (CDC, 2006a). Six of the fifteen deaths indirectly related to the hurricane and its immediate aftermath in Alabama were associated with preexisting cardiovascular disease (CDC, 2006c), and the storm disrupted an estimated 100,000 diabetic evacuees across the region from obtaining appropriate care and medication (Cefalu *et al.*, 2006). One study suggested that the hurricane had a negative effect on reproductive outcomes among pregnant women and infants, who experienced exposure to environmental toxins, limited access to safe food and water, psychological stress, and disrupted health care (Callaghan *et al.*, 2007). Other vulnerable individuals included those without personal means of transportation and poor residents in Louisiana and Mississippi who were unable to evacuate in time (U.S. CHSGA, 2006).

Box 2.2 Heatwave Early Warning Systems

Projections for increases in the frequency, intensity and duration of heatwaves suggests more cities need heatwave early warning systems, including forecasts coupled with effective response options, to warn the public about the risks during such events (Meehl and Tebaldi 2004). Prevention programs designed to reduce the toll of hot weather on the public have been instituted in several cities, and guidance has been developed to further aid communities seeking to plan such interventions, including buddy systems, cooling centers, and community preparedness (EPA 2006b). Although these systems appear to reduce the toll of hot weather (Ebi *et al.*, 2004; Ebi and Schmier 2005; Weisskopf *et al.*, 2002), and enhanced preparedness following events such as the 1995 heatwaves in Chicago and elsewhere, a survey of individuals 65 or older in four North American cities (Dayton, OH; Philadelphia, PA; Phoenix, AZ; and Toronto, Ontario, Canada) found that the public was unaware of appropriate preventive actions to take during heatwaves (Sheridan 2006). Although respondents were aware of the heat warnings, the majority did not consider they were vulnerable to the heat, or did not consider hot weather to pose a significant danger to their health. Only 46% modified their behavior on the heat advisory days. Although many individuals surveyed had access to home air-conditioning, their use of it was influenced by concerns about energy costs. Precautionary steps recommended during hot weather, such as increasing intake of liquids, were taken by very few respondents (Sheridan 2006). Some respondents reported using a fan indoors with windows closed and no air-conditioning, a situation that can increase heat exposure and be potentially deadly. Further, simultaneous heat warnings and ozone alerts were a source of confusion, because recommendations not to drive conflicted with the suggestion to seek cooler locations if the residence was too warm. Critical evaluation is needed of heatwave early warning systems, including which components are effective and why (Kovats and Ebi 2006; NOAA 2005).

Box 2.3: Quick Tips for Responding to Excessive Heat waves

For the Public

Do

- Use air conditioners or spend time in air-conditioned locations such as malls and libraries
- Use portable electric fans to exhaust hot air from rooms or draw in cooler air
- Take a cool bath or shower
- Minimize direct exposure to the sun
- Stay hydrated – regularly drink water or other nonalcoholic fluids
- Eat light, cool, easy-to-digest foods such as fruit or salads
- Wear loose fitting, light-colored clothes
- Check on older, sick, or frail people who may need help responding to the heat
- Know the symptoms of excessive heat exposure and the appropriate responses.

Don't

- Direct the flow of portable electric fans toward yourself when room temperature is hotter than 90°F
- Leave children and pets alone in cars for any amount of time
- Drink alcohol to try to stay cool
- Eat heavy, hot, or hard-to-digest foods
- Wear heavy, dark clothing.

Useful Community Interventions

For Public Officials

Send a clear public message

- Communicate that EHEs [extreme heat event] are dangerous and conditions can be life-threatening. In the event of conflicting environmental safety recommendations, emphasize that health protection should be the first priority.

Inform the public of anticipated EHE conditions

- When will EHE conditions be dangerous?
- How long will EHE conditions last?
- How hot will it feel at specific times during the day (*e.g.,* 8 a.m., 12 p.m., 4 p.m., 8 p.m.)?

Assist those at greatest risk

- Assess locations with vulnerable populations, such as nursing homes and public housing
- Staff additional emergency medical personnel to address the anticipated increase in demand
- Shift/expand homeless intervention services to cover daytime hours
- Open cooling centers to offer relief for people without air conditioning and urge the public to use them.

Provide access to additional sources of information

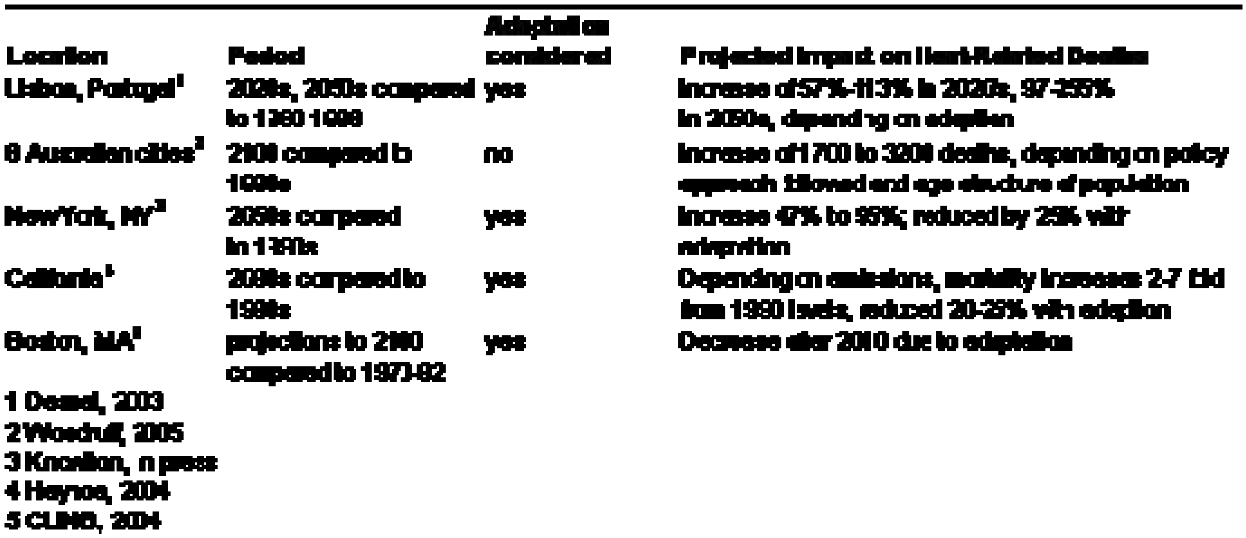
- Provide toll-free numbers and Web site addresses for heat exposure symptoms and responses
- Open hotlines to report concerns about individuals who may be at risk

- Coordinate broadcasts of EHE response information in newspapers and on television and radio.

Source: U.S. EPA, 2006

2.10 Tables

Table 2.1 Projections of Impacts of Climate Change on Heat-Related Mortality



Location	Period	Adaptation considered	Projected impact on Heat-Related Deaths
Lisbon, Portugal[1]	2020s, 2050s compared to 1980 1998	yes	Increase of 57%-113% in 2020s, 97-255% in 2050s, depending on adaption
6 Australian cities[2]	2100 compared to 1990s	no	Increase of 1700 to 3200 deaths, depending on policy approach followed and age structure of population
New York, NY[3]	2050s compared to 1990s	yes	Increase 47% to 95%; reduced by 25% with adaptation
California[4]	2090s compared to 1990s	yes	Depending on emissions, mortality increases 2-7 fold from 1990 levels, reduced 20-25% with adaption
Boston, MA[5]	projections to 2100 compared to 1970-92	yes	Decrease after 2010 due to adaptation

1 Dessai, 2003
2 Woodruff, 2005
3 Knowlton, in press
4 Hayhoe, 2004
5 CLIMB, 2004

The impacts projected for Lisbon were more sensitive to the choice of regional climate model than the method used to calculate excess deaths, and the author described the challenge of extrapolating health effects at the high end of the temperature distribution, for which data are sparse or nonexistent (Dessai 2003).

Table 2.2. Possible Influence of Climate Change on Climate Susceptible Pathogens and/or Disease, Based on Observational Models or Empirical Evidence

Pathogen	Climate Related Driver	Possible Influence of Climate Change	Likelihood of Change[a]	Basis for Assessment	References
Bacteria					
Salmonella	Rising Temperature	Increasing temperature associated with increasing clinical cases	Likely	Likelihood of climate event is high and published research supports disease trend	D'Souza *et al.*, 2004; Kovats *et al.*, 2004a; Fleury *et al.*, 2006; Naumova *et al.*, 2006
	Changes in Precipitation	Precipitation and run-off associated with increased likelihood of contamination of surface waters used for recreation, drinking or irrigation.	Likely	Likelihood of climate event is probable but more research is needed to confirm disease trend	Haley 2006; Holley *et al.*, 2006
	Shifts in Reservoir Host Ranges	Shifts in habitat and range of reservoir hosts may influence exposure routes and/or rate of contact with humans	More likely than not	Likelihood of climate event is probable but there is insufficient research on this relationship	Srikantiah *et al.*, 2003
Campylobacter	Rising Temperature	Increasing temperatures may expand typical peak season of clinical infection, or result in earlier peak (commonly spring and summer)	More likely than not	Likelihood of climate event is high and published research supports disease trend, but mechnisms are not understood	Skelly & Weinstein, 2003; Louis *et al.*, 2005; Kovats *et al.*, 2005
		Increasing temperatures may result in shorter developmental times for flies, contributing to increased transmission by this proposed vector	About as likely as not	Likelihood of climate event and fly development trend is high but additional research is needed to confirm disease association	Nichols, 2005

	Changes in Precipitation	Increasing precipitation and run-off associated with increased likelihood of contamination of surface waters used for recreation or drinking	More likely than not	Likelihood of climate event is probable but more research is needed to confirm disease trend	Auld *et al.*, 2004; Vereen *et al.*, 2007
	Shifts in Reservoir Host Ranges or Behavoir	Shifts in habitat and range of reservoir hosts (geographically or temporally) may influence exposure routes and/or rate of contact with humans	More likely than not	Likelihood of climate event is probable but there is insufficient research on this relationship	Stanley *et al.*, 1998; Lacey, 1993; Southern *et al.*, 1990
Vibrio species	Rising Temperature	Increasing ambient temperatures associated with growth in pre-harvest and post-harvest shellfish (in absence of appropriate post-harvest controls) and increasing disease	Very likely	Likelihood of climate event is high and evidence supports growth trend in ambient waters; adaptive (control) measures (refrigeration) would reduce this effect for post-harvest oysters	Cook, 1994
		Increasing temperature associated with higher environmental prevalence and disease	Extremely likely	Likelihood of climate event is high and evidence is supports environmental growth trend	Janda *et al.*, 1988; Lipp *et al.*, 2002; McLaughlin *et al.*, 2005; Dziuban *et al.*, 2006
		Increasing temperature associated with range expansion	Very likely	Likelihood of climate event is high and evidence collected to date supports trend; more data needed to confirm	McLaughlin *et al.*, 2005
	Changes in Precipitation	Increasing precipitation and fresh water run off leads to depressed estuarine salinities and increase in some *Vibrio* species	About as likely as not	Likelihood of climate event is probable but additional research is needed to confirm pathogen distribution patterns	Lipp *et al.*, 2001b; Louis *et al.*, 2003
	Sea Level Changes	Rising sea level and or storm surge increase range and human exposure	Likely	Likelihood of climate event is probable but confirmatory	Lobitz *et al.*, 2000

				research is needed on disease patterns	
Leptospira	Rising Temperature	Increasing temperatures may increase range of pathogen (temporally and geographically)	Likely	Likelihood of climate event is high but additional research is needed to confirm pathogen distribution patterns	Bharti *et al.*, 2003; Howell and Cole, 2006
	Changes in Precipitation	Increasing precipitation and run off precedes outbreaks	Likely	Likelihood of climate event in probable and research supports this pattern	Meites *et al.*, 2004
Viruses					
Enteroviruses	Rising Temperature	Increasing temperature associated with increased or expanded peak clinical season (summer)	Unlikely	Likelihood of climate event is high but no mechanistic studies are available to explain the underlying cause of this seasonality.	Khetsuriani *et al.*, 2006
		Increasing temperature associated with increased decay and inactivation of viruses in the environment	About as likely as not	Likelihood of climate event is high and research demonstrates decreased persistence under increasing temperatures but little data are available to relate this with disease	Gantzer *et al.*, 1998; Wetz *et al.*, 2004
	Changes in Precipitation	Increasing precipitation associated with increased loading of viruses to water and increased exposure or disease	Likely	Likelihood of climate is probable and research supports this pattern	Lipp *et al.*, 2001a; Frost *et al.*, 2002; Fong *et al.*, 2005
Norovirus	Rising Temperature	Increasing temperature leads to decreased retention of virus in shellfish	Unlikely	Likelihood of climate event is high and research indicates seasonally high shellfish loading in winter but there is no evidence for direct control of temperature on seasonality of infection	Burkhardt and Calci, 2000
		Increasing temperature associated with shorter peak clinical season (winter)	Unlikely	Likelihood of climate event is high and research indicates seasonal disease peak in winter but there is	Mounts *et al.*, 2000

				no evidence for direct control of temperature on seasonality of infection	
		Increasing temperature associated with increased decay and inactivation of viruses in the environment	About as likely as not	Likelihood of climate event is high and research demonstrates decreased persistence under increasing temperatures but little data are available to relate this with disease	Griffin *et al.*, 2003
	Changes in Precipitation	Increasing precipitation associated with increased loading of viruses to crops and fresh produce	More likely than not	Likelihood of climate event is probable but there is insufficient research on this relationship	Miossec *et al.*, 2000
		Increasing precipitation associated with increased loading of viruses to water and increased exposure or disease	Likely	Likelihood of climate is probable and research supports this pattern	Goodman *et al.*, 1982
Rotavirus	Rising Temperature	Increasing temperature associated with increased decay and inactivation of viruses in the environment	About as likely as not	Likelihood of climate event is high and research demonstrates decreased persistence under increasing temperatures but little data are available to relate this with disease	Rzezutka and Cook, 2004
		Dampening of winter seasonal peak in temperate latitudes	About as likely as not	Likelihood of climate event is high and research indicates seasonal disease peak in winter but there is no evidence for direct control of temperature on seasonality of infection; although tropical countries do not exhibit a seasonal peak	Cook *et al.*, 1990
Parasites					
Naegleria fowleri	Rising Temperature	Increasing temperature associated with expanded range and conversion to flagellated	More likely than not	Likelihood of climate event is high but more research is	Cabanes *et al.*, 2001

		form (infective)		needed to confirm disease trend	
Cryptosporidium	Rising Temperature	Expanding recreational (swimming) season may increase likelihood of exposure and disease	About as likely as not	Likelihood of climate event is high but there is insufficient research on this relationship	Naumova *et al.*, 2006
	Changes in Precipitation	Increasing precipitation associated with increased loading of parasite to water and increased exposure and disease	Very likely	Likelihood of climate event is probable and research supports this pattern but adaptive measures (water treatment and infrastructure) would reduce this effect	Curriero *et al.*, 2001; Davies *et al.*, 2004
Giardia	Rising Temperature	Expanding recreational (swimming) season may increase likelihood of exposure and disease	About as likely as not	Likelihood of climate event is high but there is insufficient research on this relationship	Naumova *et al.*, 2006
	Changes in Precipitation	Increasing precipitation associated with increased loading of parasite to water and increased disease	Very likely	Likelihood of climate event is probable and research supports this pattern but adaptive measures (water treatment and infrastructure) would reduce this effect	Kistemann *et al.*, 2002
	Shifts in Reservoir Host Ranges or Behavoir	Increasing temperature associated with shifting range in reservoir species (carriers) and expanded disease range	About as likely as not	Likelihood of climate event is probable but there is insufficient research on this relationship	Parkinson and Butler, 2005

[a] Likelihood was based on expert judgment of the strength of the research and the likelihood of the event. See Chapter 1 for a discussion of likelihood (section 1.5).

Table 2.3. Climate-Sensitive Health Outcomes and Particularly Vulnerable Groups

Climate-Sensitive Health Outcome	Particularly Vulnerable Groups
Heat-Related Illnesses and Deaths	Elderly, chronic medical conditions, infants and children, pregnant women, urban and rural poor, outdoor workers
Diseases and Deaths Related to Air Quality	Children, pre-existing heart or lung disease, diabetes, athletes, outdoor workers
Illnesses and Deaths Due to Extreme Weather Events	Poor, pregnant women, chronic medical conditions, mobility and cognitive constraints
Water- and Foodborne Illness	Immunocompromised, elderly, infants; specific risks for specific consequences (*e.g.*, *Campylobacter* and Guillain-Barre syndrome, *E. coli* O157:H7)
Vectorborne Illnesses	
A. Lyme Disease	Children, outdoor workers
B. Hantavirus	Rural poor, occupational groups
C. Dengue	Infants, elderly
D. Malaria	Children, immunocompromised, pregnant women, genetic (*e.g.*, G6PD status)

Table 2.4: Actors and Their Roles and Responsibilities for Adaptation to Climate Change Health Risks

Actor	**Reduce Exposures**	**Prevent Onset of Adverse Health Outcomes**	**Reduce Morbidity and Mortality**
Extreme Temperature and Weather Events			
Individuals	Stay informed about impending weather events Follow guidance for emergency preparedness	Follow guidance for conduct during and following an extreme weather event (such as seeking cooling centers during a heatwave or evacuation during a hurricane)	Seek treatment when needed
Community, State, and National Agencies	Provide scientific and technical guidance for building and infrastructure standards Enforce building and infrastructure standards, including identification of restricted building zones where necessary	Develop scientific and technical guidance and decisions support tools for development of early warning systems and emergency response plans, including appropriate individual behavior Implement early warning systems and emergency response plans Conduct tests of early warning systems and response plans before events Conduct education and outreach on emergency preparedness	Ensure that emergency preparedness plans include medical services Improve programs to monitor the air, water, and soil for hazardous exposures Improve surveillance programs to collect, analyze, and disseminate data on the health consequences of extreme events and heatwaves Monitor and evaluate the effectiveness of systems
NGOs and Other Actors		NGOs and other actors play critical roles in emergency preparedness and disaster relief	Education and training of health professionals on risks from extreme weather events
Vectorborne and Zoonotic Diseases			
Individuals	Take appropriate actions to reduce exposure to infected vectors, including eliminating vector breeding sites around residence	Vaccinate for diseases to which one would likely be exposed	Seek treatment when needed

Community, State, and National Agencies	Provide scientific and technical guidance and decision support tools for development of early warning systems Conduct effective vector (and pathogen) surveillance and control programs (including consideration of land use policies that affect vector distribution and habitats) Develop early warning systems for disease outbreaks, such as West Nile virus Develop and disseminate information on appropriate individual behavior to avoid exposure to vectors	Conduct research on vaccines and other preventive measures Conduct research and development on rapid diagnostic tools Provide vaccinations to those likely to be exposed	Conduct research on treatment options Develop and disseminate information on signs and symptoms of disease to guide individuals on when to seek treatment
Waterborne and Foodborne Diseases			
Individuals	Follow proper food-handling guidelines Follow guidelines on drinking water from outdoor sources		Seek treatment when needed
Community, State, and National Agencies	Improve surveillance and control programs for early detection of disease outbreaks Develop methods to ensure watershed protection and safe water and food handling (*e.g.*, Clean Water Act)	Sponsor research and development on rapid diagnostic tools for food- and waterborne pathogens	Sponsor research and development on treatment options Develop and disseminate information on signs and symptoms of disease to guide individuals on when to seek treatment
Diseases Related to Air Quality			
Individuals	Follow advice on appropriate behavior on high ozone days	For individuals with certain respiratory diseases, follow medical advice during periods of high air pollution	Seek treatment when needed

Community, State, and National Agencies	Develop and enforce regulations of air pollutants (*e.g.*, Clean Air Act)	Develop decision support tools for early warning systems Conduct education and outreach on the risks of exposure to air pollutants	Conduct research on treatment options

Table 2.5: Adaptation Measures to Reduce Climate Change-Related Health Risks

	Heatwaves	Extreme Weather Events	Vectorborne Diseases	Waterborne Diseases	Air Quality
Decision Support Tools	Enhance early warning systems	Enhance early warning systems and emergency response plans	Enhance early warning systems based on climate and environmental data for selected diseases	Develop early warning systems based on climate and environmental data for conditions that may increase selected diseases	Enhance alert systems for high air pollution days
Technology Development	Improve building design to reduce heat loads during summer months		Develop vaccines for West Nile virus and other vectorborne diseases Develop more rapid diagnostic tests	Develop more rapid diagnostic tests	
Surveillance and Monitoring	Alter health data collection systems to monitor for increased morbidity and mortality during a heatwave	Alter health data collection systems to monitor for disease outbreaks during and after an extreme event	Enhance vector surveillance and control programs Monitor disease occurrence	Enhance surveillance and monitoring programs for waterborne diseases	Enhance health data collection systems to monitor for health outcomes due to air pollution
Infrastructure Development	Improve urban design to reduce urban heat islands by planting trees, increasing green spaces, etc.	Design infrastructure to withstand projected extreme events	Consider possible impacts of infrastructure development, such as water storage tanks, on vectorborne diseases	Consider possible impacts of placement of sources of water- and foodborne pathogens (*e.g.*, cattle near drinking water sources)	Improve public transit systems to reduce traffic emissions
Other	Conduct research on effective approaches to encourage appropriate behavior during a heatwave	Conduct research on effective approaches to encourage appropriate behavior during an extreme event			

2.11 Figures

Figure 2.1. Temperature-mortality relative risk functions for 11 U.S. cities, 1973–1994. Northern cities: Boston, Massachusetts; Chicago, Illinois; New York, New York; Philadelphia, Pennsylvania; Baltimore, Maryland; and Washington, DC. Southern cities: Charlotte, North Carolina; Atlanta, Georgia; Jacksonville, Florida; Tampa, Florida; and Miami, Florida. Relative risk is defined as the risk of an event such as mortality relative to exposure, such that the relative risk is a ratio of the probability of the event occurring in the exposed group versus the probability of occurrence in the control (non-exposed) group.

(Curriero *et al.*, 2002)

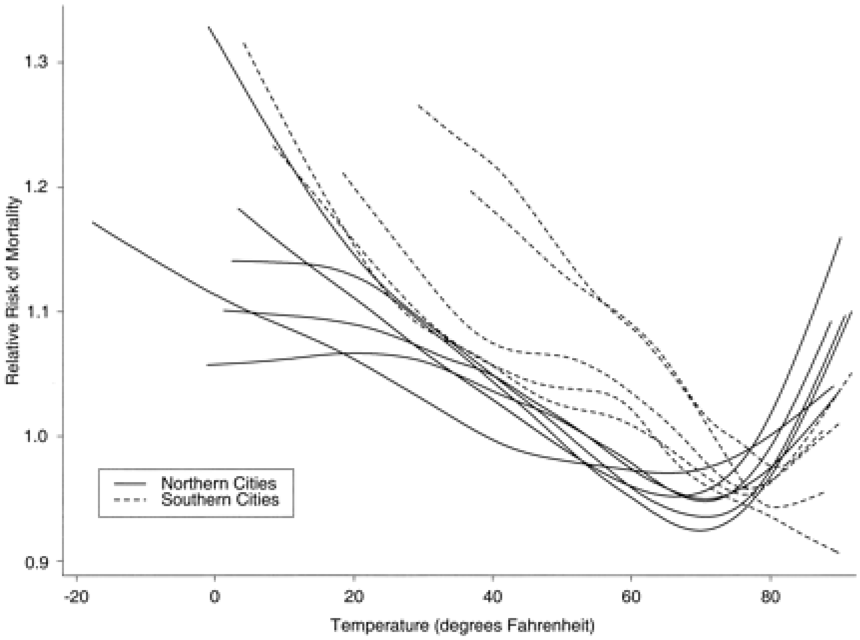
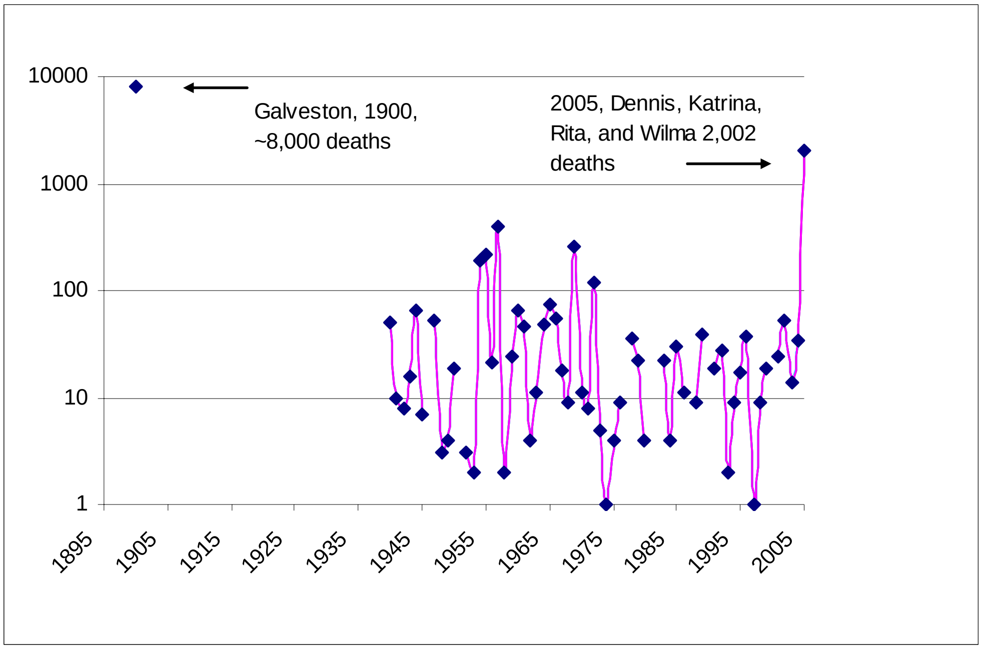
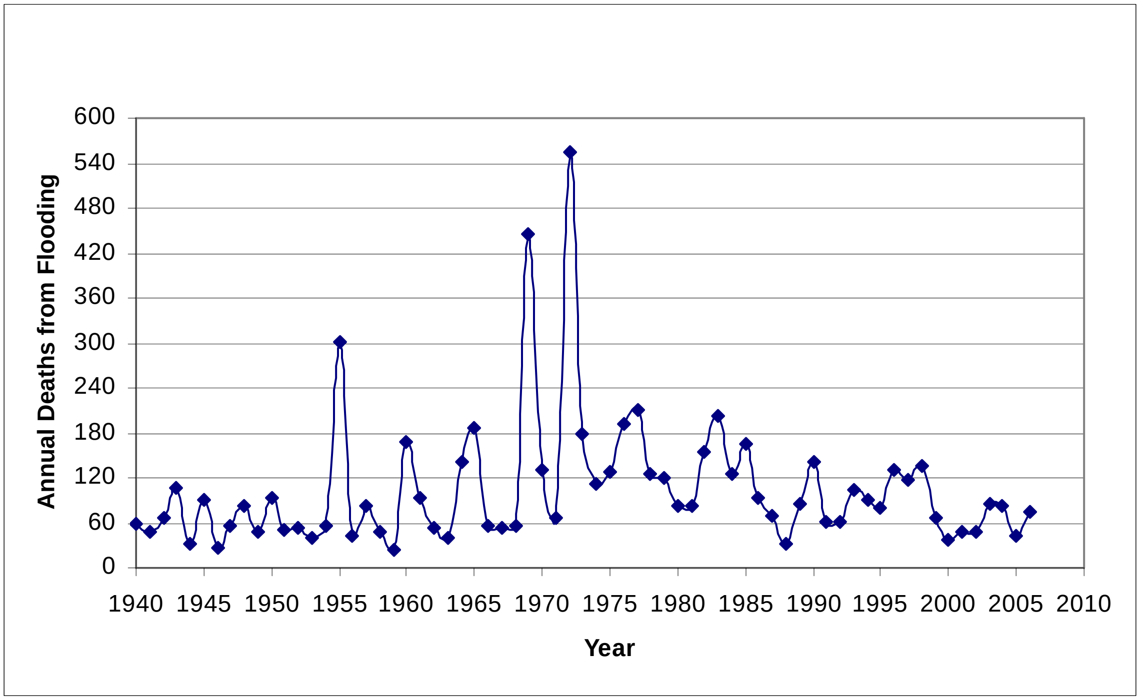


Figure 2.2. Annual Deaths Attributed to Hurricanes in the United States, 1900 and 1940-2005



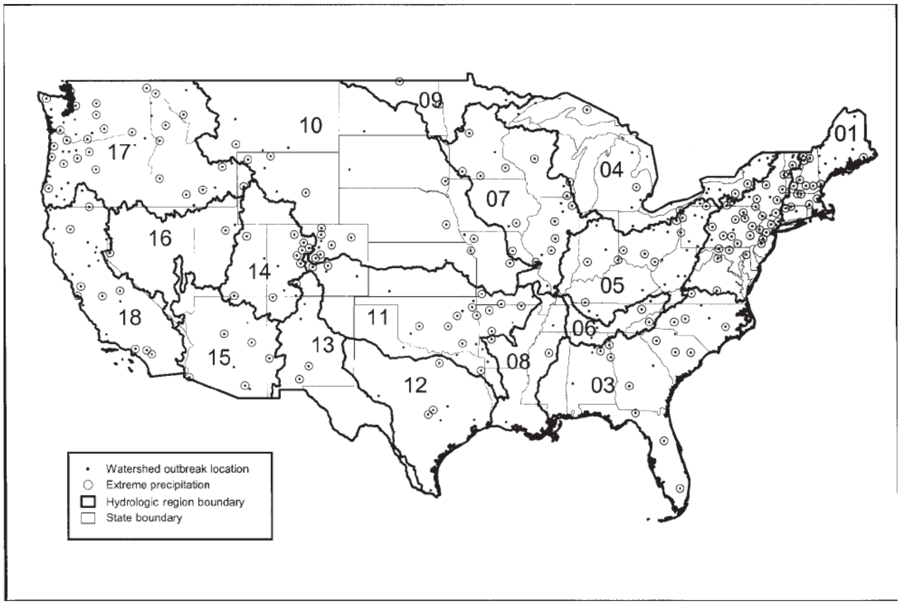
Source: NOAA, 2007

Figure 2.3. Annual Deaths Attributed to Flooding in the United States, 1940-2005



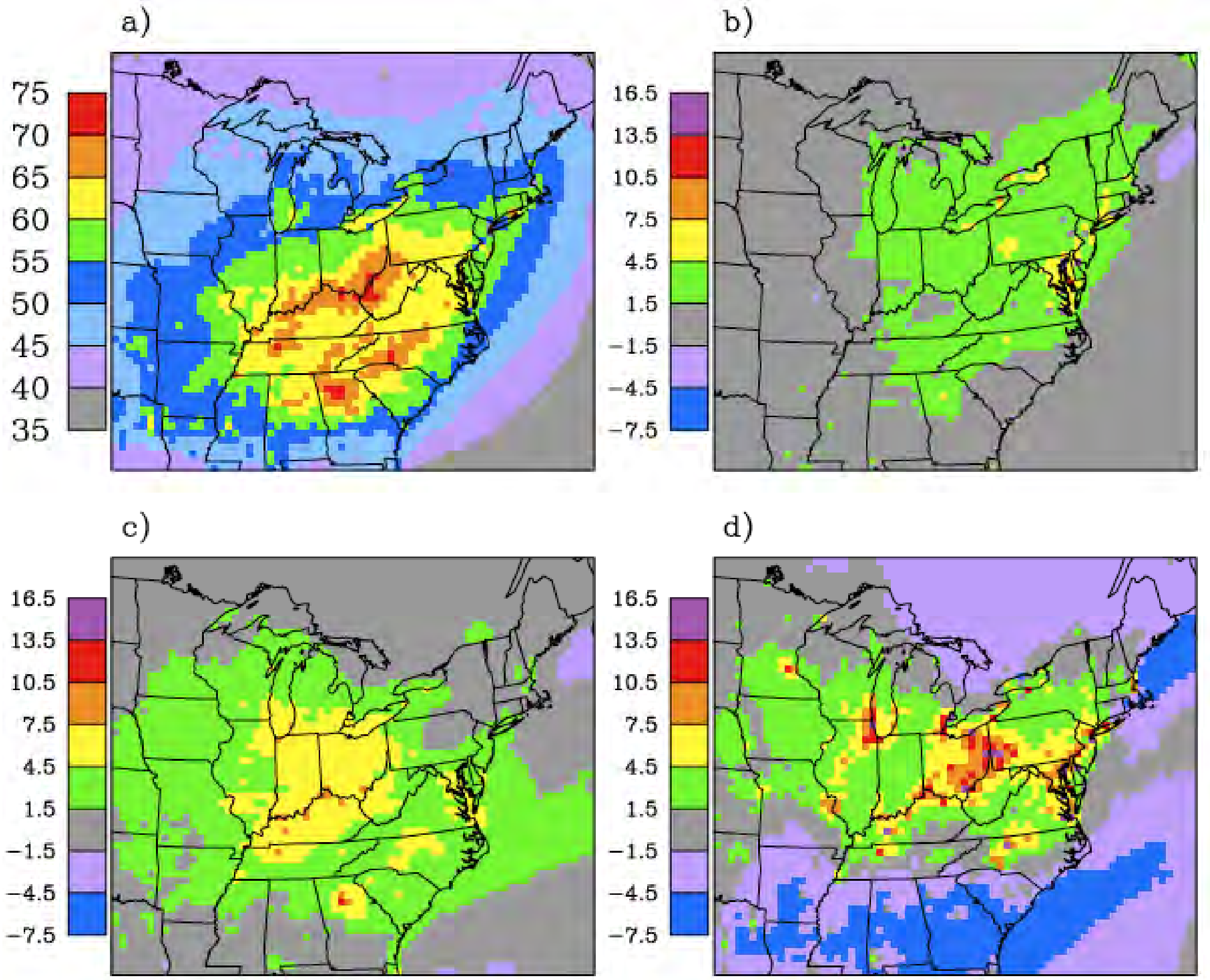
Source: NOAA, 2007a

Figure 2.4. Drinking Waterborne Disease Outbreaks and 90%-ile Precipitation Events (a two month lag precedes outbreaks); 1948 – 1994.



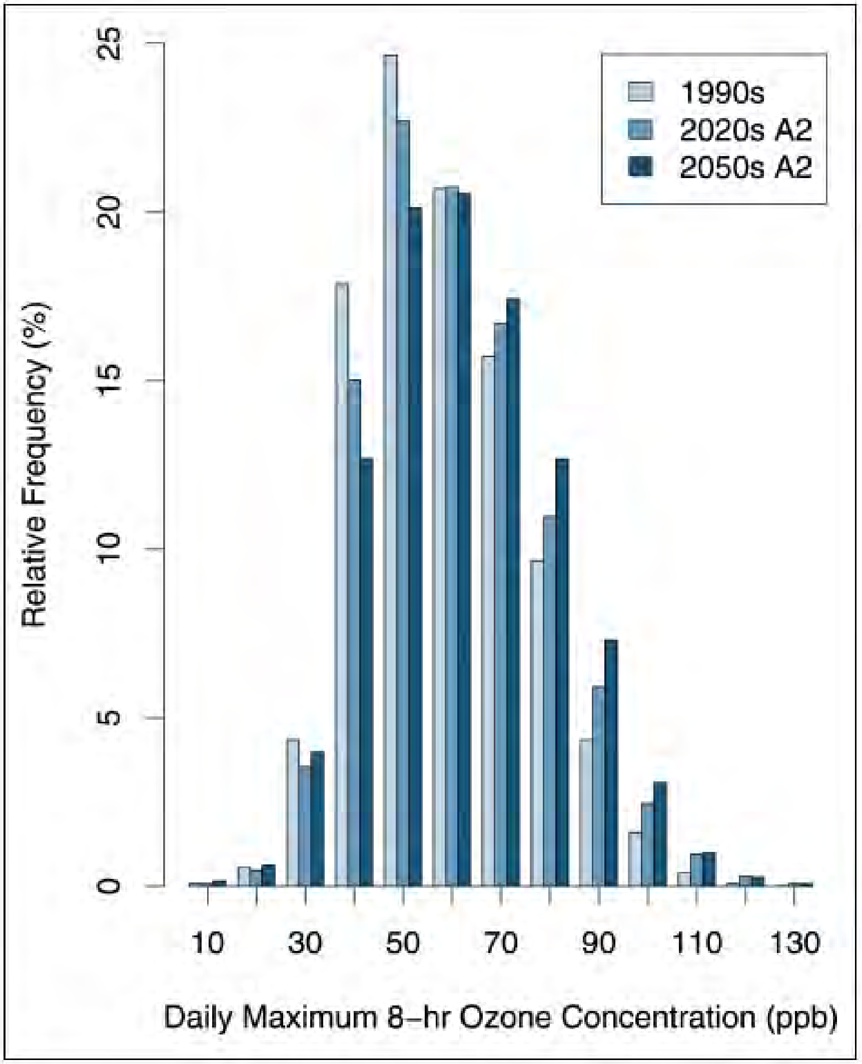
Source: Curriero *et al.*, 2001

Figure 2.5: (a) Summertime Average Daily Maximum 8-hour Ozone Concentrations (ppb) for the 1990s and Changes for the (b) 2020s relative to the 1990s, (c) 2050s relative to the 1990s, and (d) 2080s relative to the 1990s. All are based on the A2 Scenario relative to the 1990s. Five consecutive summer seasons were simulated in each decade.



Source: Hogrefe *et al.*, 2004a.

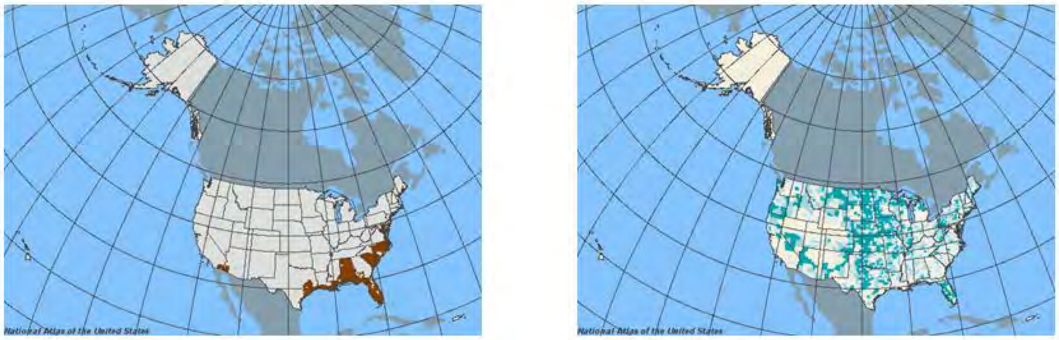
Figure 2.6. Frequency Distributions of Summertime Daily Maximum 8-hr Ozone Concentrations over the eastern United States in the 1990s, 2020s, and 2050s based on the A2 Scenario.



Source: From Hogrefe *et al.*, 2005a

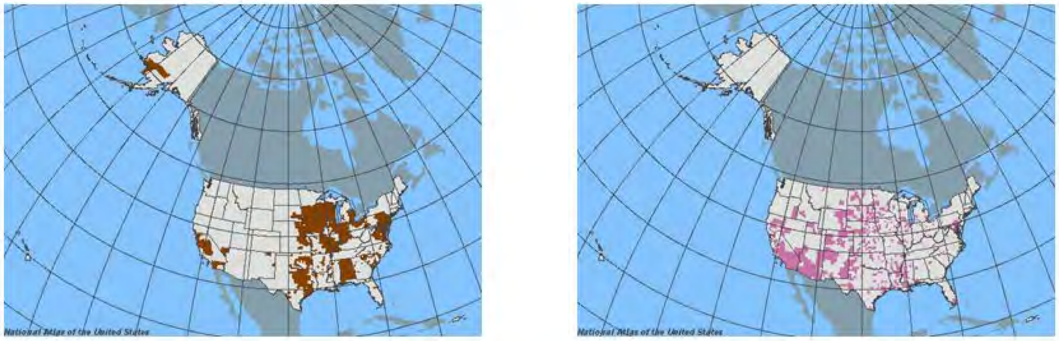
Figure 2.7.a-d. U.S. maps indicating counties with existing vulnerability to climate sensitive health outcomes: (a) location of hurricane landfalls; (b) extreme heat events, defined by CDC as temperatures 10 or more degrees above the average high temperature for the region and lasting for several weeks; (c) percentage of population over age 65; (d) West Nile Virus cases reported in 2004. Historical disease activity, especially in the case of WNV, is not necessarily predictive of future vulnerability. Maps were generated using NationalAtlas.gov™ Map Maker (2008).

Geographic Vulnerability of US Residents
to Selected Climate Related Health Impacts



Location of Hurricane Landfalls, 1995-2000

Percentage of US Population 65 or older, 2000



Locations of Extreme Heat Events, 1995-2000

West Nile Virus Cases, 2004