Synthesis and Assessment Product 4.6

Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems

Executive Summary

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Abstract

Climate change, interacting with changes in land use and demographics, has the capacity to affect important human dimensions in the United States, especially related to human health, human settlements and human welfare. The challenges presented by population growth, an aging population, migration patterns, and urban and coastal development are likely to be compounded by changes in temperature, precipitation, and extreme climate-related events. Climate change will affect where people choose to live, work, and play. Even wealthy societies, like the United States, will be subject to climate impacts. Climate change will affect individuals and communities including impacts related to variation in rainfall, more intense downpours, more frequent heat waves, severe drought conditions with associated water shortages, changes in minimum and maximum temperatures, potential increases in the intensity and frequency of extreme tropical storms, measurable sea-level rise and increases in the occurrence of coastal and riverine flooding. In response to these anticipated changes, the United States is expected to develop and deploy strategies for mitigating greenhouse gases and for adapting to the individual and collective impacts of climate change.

This report – the Synthesis and Assessment Product 4.6 (SAP 4.6) – focuses on how climate change affects what people care most about. It analyzes the impacts of global change, especially those of climate variability and change and of land use and population dynamics, on three broad dimensions of the human condition: human health, human settlements, and human welfare. The SAP 4.6 has been prepared by a team of experts from academia, government, and the private sector in response to the mandate of the U.S. Climate Change Science Program's *Strategic Plan* (2003). The assessment examines potential impacts of climate change on human society, opportunities for adaptation, and associated recommendations for addressing data gaps and near- and long-term research goals.

Survey of Important Findings

Climate variability and change challenge even the world's most advanced societies. At a very basic level, climate affects the costs of providing comfort in our homes and work places. A favorable climate also provides inputs for a good life: adequate fresh water supplies; products from the ranch, the farm, the forests, the rivers and the coasts; pleasure derived from tourist destinations and from nature, biodiversity, and outdoor recreation. Climate not only provides goods and services, but also affects the spread of some diseases and the prevalence of other health problems. It is also associated with threats from extreme events and natural disasters such as tropical storms, riverine and coastal flooding, fires, droughts, wind, hail, ice, heat, and cold.

Table ES.1 Impacts of Climate Variability and Change on Human Health, Human Settlements, and Human Welfare in the United States

Focus Area	Climate factor	Impact	Assessment	Adaptation Strategies
HUMAN HEALTH				
	Extreme temperatures	Heat stress/stroke or hypothermia	Very likely in Midwest and northeast urban centers	Early watch and warning systems and installation of cooling systems in residential and commercial buildings
	Increase in precipitation	Contaminated water and food supplies with associated gastrointestinal illnesses, including salmonella and giardia	Likely in areas with out-dated or over-subscribed water treatment plants	Improve infrastructure to guard against combined sewer overflow; public health response to include "boil water" advisories
	Hurricane and storm surge	Injuries from flying debris and drowning / exposure to contaminated flood waters and to mold and mildew / exposure to carbon monoxide poisoning from portable generators	Likely in coastal zones of the southeast Atlantic and the Gulf Coast	Public health advisories in immediate aftermath of storm; coordinate storm relief efforts to insure that people receive necessary information for safeguarding their health
	Devastating storm events	Post-traumatic stress disorder and related anxiety and depression	Likely in instances of extreme storm events, such as was seen in the aftermath of Hurricane Katrina	Public health response should include identification of persons in need of mental health care; response should coordinate local service providers and emergency providers
	Air pollution aggravated by temperature-related increases in ozone and aeroallergens	Cardiovascular and pulmonary illnesses, including exacerbation of asthma and chronic obstructive pulmonary disorder (COPD)	Very likely in urban centers in the west, the southwest, the mid-Atlantic and the northeast	Public warning via air quality action days; encourage use of alternative fuels in vehicles and in personal and commercial HVAC systems
	Air pollution degraded by wildfire	Asthma and COPD aggravated	Likely in California, the southwest and the southeast	Public health air quality advisories

HUMAN SETTLEMENTS				
	Extreme temperatures	Increase energy demand	Very likely	Expand capacity for heating and cooling through public utilities; invest in alternative energy sources
	Drought	Strain on municipal and agricultural water supplies	Very likely in intermountain west, desert southwest, and southeast	Identify new sources through development of reservoirs; encourage conservation of water for personal and public use
	Hurricane and storm surge	Disruption of infrastructure, including levee systems, river channels, bridges, and highway systems; disruption of residential neighborhoods	Very likely in southeast Atlantic Coast and Gulf Coast	Harden coastal zones or retreat or relocate; insure against catastrophic loss due to flooding and high winds
	Wildfires	Disruption of communities and property destruction	Very likely in intermountain west, desert southwest, and southeast	Clear vegetation away from buildings; issue emergency evacuation orders
	Late snow fall and early snow melt	Disruption of water supplies for municipal and agricultural use	Very likely in intermountain west	Build reservoirs; conserve water supplies; divert supply from agricultural to municipal use
HUMAN WELFARE				
	Extreme temperatures	Discomfort; limit some outdoor activities / recreation	Very likely in more northern latitudes of the United States	Public health watch/warning advisories
	Late snow fall and early snow melt	Limit some snow-related recreational opportunities	Very likely in intermountain west	Engage in alternative recreation activities
	Extreme precipitation events	Local flooding and contamination of water supplies	Very likely nationwide	Issue flood advisories / warnings
	Hurricane and coastal storms	At-risk properties experience flood and wind damage; individuals experience disruption to daily life	Very likely in coastal zone of the Gulf Coast and the southern Atlantic	Purchase flood insurance to limit personal exposure to catastrophic loss

Climate variability and change interact with existing and changing settlement patterns. In the United States, we have seen shifts of population from frost-belt to sun-belt, the movement of households from urban centers to far flung suburbs, an overall loss of population in some urban centers in the Midwest and Northeast, and rapid growth in the metropolitan areas of the South and West. Additionally, the proliferation of information technologies and declining costs of airline travel have made previously remote locations more accessible for work or retirement. Together, these trends dramatically alter anticipated impacts from climate because they fundamentally shape the nature and scope of human vulnerability. Understanding the impacts of climate change and variability on the quality of life in U.S. communities implies knowledge of how these dynamics vary by location, time, and socioeconomic group. The following summary examines a range of climate-related impacts on critical human systems, including: human health, human settlements, and human welfare.

Summary of Effects of Climate on Human Health.

The United States is a developed country with a temperate climate. There will likely be fewer cases of illness and death resulting from climate change than expected in the developing world for a number of reasons. First, greater wealth and more developed infrastructure enhance our ability to respond to changes. In particular, the well-developed public health and medical care infrastructures, along with the involvement of government agencies and non-governmental organizations in disaster planning and response are key assets that will allow the U.S. to adapt to some of the health effects associated with climate change.

It is very likely that the burden of heat-related morbidity and mortality will increase over coming decades. 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). Older adults are vulnerable to temperature extremes. This suggests that temperature-related morbidity and mortality are likely to increase. Heat-related mortality affects poor and minority populations disproportionately, in part due to lack of air conditioning. In fact, the concentration of poverty in inner city neighborhoods leads to disproportionate adverse effects related to urban heat islands.

The impacts of higher temperatures in urban areas and associated increases in tropospheric ozone concentrations are likely to cause or exacerbate cardiovascular and pulmonary illness. In addition, stagnant air masses related to climate change are likely to increase air pollution in some local areas. Physical features of communities, including housing quality and green space, social programs that affect access to health care, aspects of population composition (level of education, racial/ethnic composition), and social and cultural factors are all likely to affect vulnerability to temperature extremes.

Hurricanes, extreme precipitation resulting in floods, and wildfires also have the potential to affect public health through direct and indirect health risks. Health risks associated with extreme events are likely to increase with the size of the population and the degree to which it is physically, mentally, or financially constrained in its ability to prepare for and respond to extreme weather events. For example, heat wave early warning systems are designed to warn the public of risks of dangerously hot ambient temperatures, but a survey of older adults found that the public was not aware of the appropriate preventive actions.

Several food and water-borne pathogens are likely to be transmitted among susceptible populations depending on the pathogens' survival, persistence, habitat range and transmission under changing climate and environmental conditions. The primary climate-related factors that may affect these pathogens include temperature, precipitation, extreme weather events, and ecological shifts. Nonetheless, climate change will seldom be the primary factor affecting the burden of climate-related injuries, illness, and death.

Health burdens related to climate change will vary by region. The northern latitudes of the United States are likely to experience the largest increases in average temperatures; they will also bear the brunt of increases in ground-level ozone and other airborne pollutants. Populations in Midwestern and Northeastern cities are likely to be disproportionately affected by heat related illnesses as heat waves increase in frequency, severity, and duration. The distributions of disease vectors are likely to widen. The range of many vectors is likely to extend northward and to higher elevations. For some vectors, such as rodents associated with Hantavirus, ranges are likely to expand, based on decreased, rather than increased, precipitation. The West Coast is likely to experience even greater demands on water supplies as regional precipitation declines and average snow packs decrease. Forest fires with their associated decrements to air quality are likely to increase in frequency, severity, distribution, and duration in the Southeast, the Intermountain West and the West.

Finally, climate change is very likely to accentuate the disparities already evident in the American health care system. Many of the expected health effects are likely to fall disproportionately on the poor, the elderly, the disabled, and the uninsured. The most important adaptation to ameliorate health effects from climate change is to support and maintain the United States' public health infrastructure.

Summary of the Effects of Climate Change on Human Settlements

Effects of climate change on human settlements are very likely to vary considerably according to location-specific vulnerabilities, with the most vulnerable areas likely to include: Alaska, flood-risk coastal zones and river basins, arid areas with associated water scarcity and areas where the economic base is climate sensitive. Except for Alaska, the main climate impacts have to do with changes in the intensity, frequency and location of extreme weather events and, in some cases, water availability rather than temperature change.

Changes in precipitation patterns will affect water supplies nationwide. Likely reductions in snowmelt, river flows, and groundwater levels, along with increases in saline intrusion into coastal rivers and groundwater will shrink fresh water supplies even as population growth taxes demand. Moreover, storms, floods, and other severe weather events are likely to affect infrastructure such as sanitation, transportation, supply lines for food and energy, and communication. Some of our most expensive infrastructure, such as exposed structures like bridges and utility networks, are especially vulnerable. In many cases, water supply networks and stressed reservoir capacity interact with growing populations (especially in coastal cities and in the Mountain and Pacific West). The complex interactions of land use, population growth and dynamics of settlement patterns further challenge supplies of water for municipal, industrial, and agricultural uses.

Hurricane Katrina flooding in New Orleans Louisiana. National Oceanic and Atmospheric Administration. www.katrina.noaa.gov/helicopter/helicopter-2.html

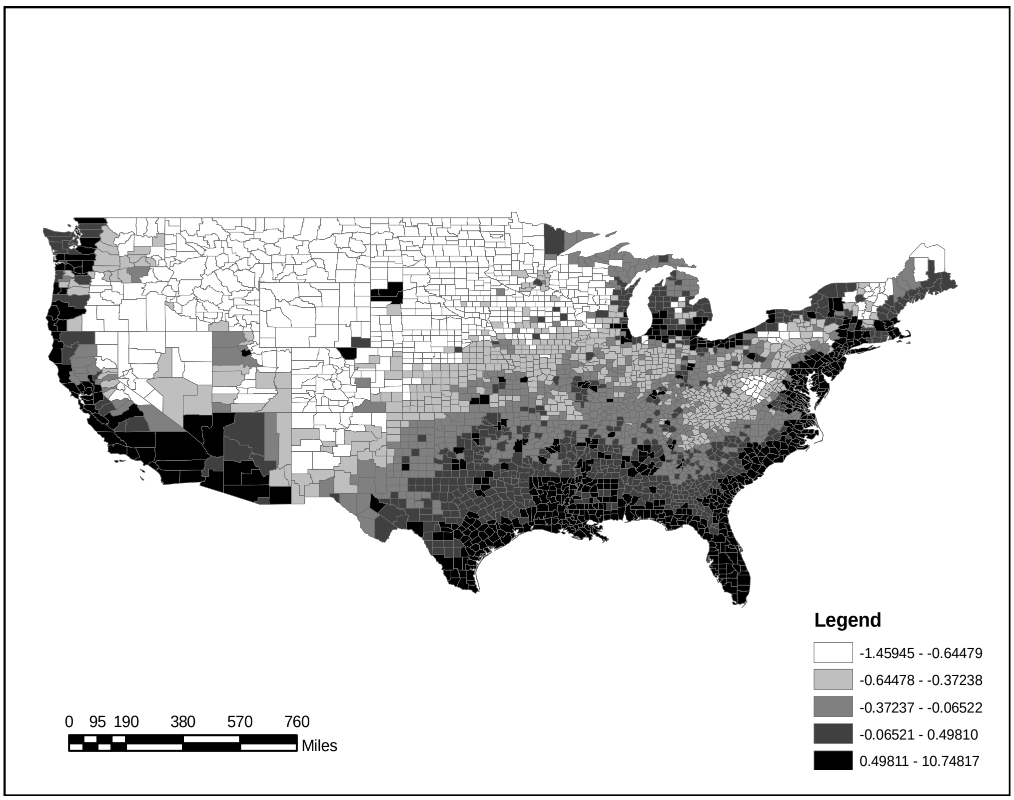
Communities in risk-prone regions have reason to be particularly concerned about any potential increase in severe weather events. The combined effects of severe storms and sea-level rise in coastal areas or increased risks of fire in drier arid areas are examples of how climate change may increase the magnitude of challenges already facing risk-prone communities. Vulnerabilities may be especially great for rapidly-growing and/or larger metropolitan areas, where the potential magnitude of both impacts and coping requirements are likely to be very large. On the other hand, such regions have greater opportunity to put more adaptable infrastructure in place and make decisions that limit vulnerability.

Warming is virtually certain to increase overall energy demand in U.S. cities (see SAP 4.5 Effects of Climate Change on Energy Production and Use in the United States). Even though some regions will have less demand related to winter heating, increased demand for cooling during unusually warm periods will most likely be larger. This increased demand is also more likely to jeopardize energy service reliability in areas where failures of the electric grid occurs more frequently in over-taxed urban systems. The increasing climate control needs in homes, schools, hospitals and commercial buildings will have inflate business and household energy costs.

Climate change has the potential not only to affect communities directly but also through undermining their economic bases. In particular, some regional economies are dependent on sectors highly sensitive to changes in climate: agriculture, forestry, water resources, or tourism. Climate change can add to stress on social and political structures by increasing management and budget requirements for public services such as public health care, disaster risk reduction, and even public safety. As sources of stress grow and combine, the resilience of social and political structures are expected to suffer, especially in locales with relatively limited social and political capital.

Finally, growth and development is generally moving toward areas more likely to be vulnerable to the effects of climate change. For example, approximately half of the U.S. population, 160 million people, will live in one of 673 coastal counties by 2008. Coastal areas – particularly those on gently-sloping coasts – should be concerned about sea level rise in the longer term, especially if they are subject to severe storms and storm surges and/or if their regions are showing gradual land subsidence. The map (figure ES.2) identifies the concentrations of highly vulnerable counties as lying along the east and west coasts and Great Lakes, with medium vulnerability counties mostly inland in the southeast, southwest, and northeast. The study uses measures of both *physical vulnerability* (expected temperature change, extreme weather events, and coastal proximity) and *adaptive capacity* (as represented by economic, demographic, and civic participation variables that constitute a locality's socioeconomic capacity to commit to costly climate change policy initiatives).

Figure ES.1 Geography of Climate Change Vulnerability at the County Scale Source: Zahran *et al.*, forthcoming.



Summary of the Effects of Climate Change on Human Welfare

The terms human welfare, quality of life, and well-being are often used interchangeably, and by a number of disciplines as diverse as psychology, economics, health science,

geography, urban planning, and sociology. Welfare is typically defined and measured as a multi-dimensional concept. Quality of life taxonomies typically converge on six dimensions: 1) economic conditions, 2) natural resources and amenities, 3) human health, 4) public and private infrastructure, 5) government and public safety and 6) social and cultural resources. Climate change will most likely have impacts across all of these dimensions – both positive and negative. In addition, the positive and negative effects of climate change will together have effects on broader communities, which are the networks of households, businesses, physical structures, and institutions located together in geographic space.

Quantifying impacts of climate change on human welfare requires linking effects in the quality of life dimensions to the projected physical effects of climate change and the consequent effects on human and natural systems. Economics provides one means of quantifying and, in some cases, placing dollar values on welfare effects. Most of the climate research, however, has not focused on quantifying linkages from climate change to specific endpoints or services, which are the foundation of welfare. In addition, even in cases where welfare effects have been quantified, it is difficult to compare and aggregate disparate effects across different sectors, because of the different metrics that each sector uses (e.g., human illness and morbidity vs. reductions in numbers of species).

This report examines four types of effects: those on ecosystems, human health, recreation, and amenities associated with climate. Some of the less tangible effects of climate change can be difficult to quantify and value, because they represent effects on good and services that are not traded in markets. For example, ecosystems provide a variety of services, including: food and fiber, regulating air and water quality, support services such as photosynthesis, and cultural services such as recreation and aesthetic or spiritual values. Ecologists have already detected or predict within this century a number of ecological impacts, including the shifting, break up, and loss of ecological communities; plant and animal extinctions and a loss in biodiversity; shifting ranges of plant and animal populations; and changes in ecosystem processes, such as nutrient cycling and decomposition.

Little research has been done linking these ecological changes to changes in services, and still less has been done to quantify, or place dollar values on, these changes. Ecosystem impacts also extend beyond the obvious direct effects within the natural environment to indirect effects on human systems. Nearly 90% of Americans take part in outdoor recreation. The length of the season of some of these activities may be favorably affected by slightly increased temperatures, however ambient conditions may eventually have adverse effects on outdoor activities like walking or beach recreation that is affected by sea level rise. Snow sports are the most obvious casualty among vulnerable recreation activities with the reduction in visitor use occurring primarily from a shorter season. But, the decrements associated with snow-based recreation are more than outweighed by increases in other outdoor activities, including boating, fishing, golf, and beach and stream recreation.

An agenda for understanding the impacts of climate change on human welfare may require taking steps both to develop a framework for addressing welfare, and to address the data and methodological gaps inherent in the estimation and quantification of effects. To that end, the study of climate change on human welfare is still developing, and, to our knowledge, no study has made a systematic survey of the full range of welfare impacts associated with climate change, much less attempted to quantify them.

Table ES.2. The regional texture of climate endpoints associated with U.S. population growth to 2030, by census region. The expected growth is concentrated in the relatively more vulnerable areas of the South Atlantic, the Gulf Coast (West South Central) and the West.

U.S. Census Region	Pop Growth by 2030 (millions)	Climate-Related Issues: Degraded summer air quality	Urban heat islands	Snowpack / snowmelt	Hurricanes	Heat wave	Extreme rainfall events	Drought	Wildfires
New England ME VT NH MA RI CT	2.0		✓	✓					
Middle Atlantic NY PA NJ	3.9	✓	✓	✓					
East North Central WI MI IL IN OH	4.2		✓			✓			
West North Central ND MN SD IA NE KS MO	3.1		✓			✓		✓	
South Atlantic WV VA MD NC SC GA FL	15.7	✓	✓		✓		✓	✓	✓
East South Central KY TN MS AL	3.3	✓	✓		✓		✓		
West South Central TX OK AR LA	10.6	✓	✓		✓	✓		✓	✓
Mountain MT ID WY NV UT CO AZ NM	7.3	✓	✓	✓		✓		✓	✓
Pacific AK CA WA OR HI	22.2	✓	✓	✓		✓	✓	✓	✓

Snowpack / snowmelt
Degraded summer air quality
Urban heat islands
Hurricanes
Extreme rainfall events
Wildfires
Drought
Heat wave

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Analyses and Effects of Global Change on Human Health and Welfare and Human Systems

Chapter 1: Introduction

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1.1 Scope and Approach of the SAP 4.6

The Global Change Research Act of 1990 (Public Law 101-606) calls for the periodic assessment of the impacts of global environmental change for the United States. In 2001, a series of sector and regional assessments were conducted by the U.S. Global Change Research Program as part of the First National Assessment. Subsequently, the U.S. Climate Change Science Program developed a *Strategic Plan* (CCSP 2003) calling for the preparation of 21 synthesis and assessment products (SAPs) to inform policy making and adaptive management across a range of climate-sensitive issues. Synthesis and Assessment Product 4.6 examines the effects of global change on human systems. This product addresses Goal 4 of five strategic goals in the CCSP *Strategic Plan* to "understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes"(CCSP 2003). The "global changes" assessed in this report include: those related to climate change, those related to climate variability and those derived from shifting patterns of land use within the United States and associated changes in the nation's population patterns. While the mandate for the preparation of this report calls for evaluating the impacts of <u>global</u> change, the emphasis throughout are those impacts associated with climate variability and change. Collectively, global changes are human problems, not simply problems for the natural or the physical world. Hence, this SAP examines the vulnerability of human health and socioeconomic systems to climate variability and change across three foci of potential impacts and adaptations: human health, human settlements and human welfare.

The report's authors included a Convening Lead Author from the Environmental Protection Agency, three Lead Authors for each of the topic chapters and a team of 28 contributing authors. The audience for this report includes public health practitioners, resource managers, urban planners, transportation planners, elected officials and other policy makers, and concerned citizens.

Chapter 2 provides a synthesis chapter specifically designed to appeal to a wide range of readers, including non-scientists, policy makers, resource managers and resource planners, interested citizens, and others who have a stake in understanding the potential consequences of climate change on human systems. Chapter 2 synthesizes findings from across Chapters 3-5, focusing on several organizing themes.

Chapters 3-5 describe the impacts of climate variability and change on human systems and outline opportunities for adaptation and associated near- and long-term research needs. SAP 4.6 addresses the questions of how and where climate variability and change may impact U.S. social systems. The challenge for this project is to derive an assessment of risks associated with health, welfare, and settlements and to develop timely adaptive strategies that address wide-ranging human vulnerabilities. Successful risk assessment classifies impacts of climate variability and change across an array of characteristics, including: the magnitude of risk (both baseline and incremental risks), the distribution of risks across populations (typical responders v. maximum-exposed individuals), and the availability, difficulty, irreversibility, and cost of adaptive alternatives. The primary goals for adaptation to climate variability and change are:

(i) To avoid maladaptive responses;

(ii) To manage significant risks proactively when possible;

(iii) To establish protocols to detect and measure risks;
(iv) To leverage technical and institutional capacity;
(v) To reduce current vulnerabilities to climate variability and change, and
(vi) To develop adaptive capacity to address new climate risks that exceed conventional adaptive measures.

Key to successful adaptation is the recognition that adaptive strategies are processes that play out across time. Needs we identify and respond to today are expected to evolve with the passage of time. Furthermore, as individuals respond to climate change they may yield substantial individual, in addition to collective, goods.

Chapter 3 assesses the potential impacts of climate variability and change on four health endpoints in the United States: water and foodborne diseases, vector and zoonotic diseases, human morbidity and mortality associated with changes in air quality, and human morbidity and mortality associated with extreme weather events and temperature extremes. For each of the health endpoints, the assessment addresses a range of topics, including:

- characterization of human health impacts from climate change in the United States;
- characterization of potential indirect effects;
- adaptation opportunities and support for effective decision making; and
- an overview of important research gaps.

The first part of the chapter focuses on the impacts of global change --- with an emphasis on those of climate variability and change --- on human morbidity and mortality. The assessment includes research published from 2001 through early 2007 in the U.S., or in Canada, Europe, and Australia, where results may provide insights for U.S. populations. The second section focuses on adaptation to the potential health impacts of climate variability and change, including public health interventions that could be revised, supplemented, or implemented to protect human health in response to the challenges and opportunities posed by climate change.

Chapter 4 focuses on the impacts and adaptations associated with climate change on human settlements in the United States. The IPCC Third Assessment Report (IPCC, 2001) concludes that settlements are among the human systems that are the most sensitive to climate change. For example, projected changes in climate extremes could have devastating consequences for human settlements that are vulnerable to droughts and wildfires, coastal and riverine floods, sea level rise and storm surge, heat waves, avalanches, land slides, and windstorms. While specific changes in these conditions cannot yet be predicted with great certainty, climate change is likely to increase the frequency and severity of some if not all of these events. Chapter 4 focuses on the interaction between settlement characteristics and climate and other global stressors, with a particular focus on urban areas and densely-developed population centers in the U.S. Because of their high population density, urban areas multiply human risk, especially where there are high percentages of the very old, the very young, the poor, the disabled and the chronically ill. In addition, because of the scale and complexity of these built environments, transportation networks, the energy and resource demands, and the interdependence of these systems and the populations they serve, urban areas are vulnerable to multiplying impacts in response to externally imposed environmental stresses. The collective vulnerability of American urban centers is expected to grow over time as a disproportionate share of urban growth is likely to concentrate population in areas like the Inter-Mountain West or the Gulf Coast. The focus of Chapter 4 is on high density and or rapidly growing settlements and the potential for changes over time in the vulnerabilities associated with their **place-based** characteristics (such as climatic regime, elevation, and proximity to coasts and rivers) and their **form-based** characteristics (such as whether development patterns are sprawling or compact).

Chapter 5 focuses on the impacts of climate variability and change on human welfare. Human welfare is an elusive concept, and there is no single, commonly-accepted definition or approach to thinking about welfare. Yet there is a shared understanding that increases in human welfare are associated with improvements in individual and group life conditions in areas such as economic power, social contacts, and opportunities for leisure and recreation along with reductions in injury, stress, and loss. The physical environment, with climate as one aspect, is among many factors that can affect human welfare via economic, physical, psychological, and social pathways that influence individual perceptions of quality of life. At a minimum, climate variability and change may result in lifestyle changes and adaptive behavior with both positive and negative welfare implications. More generally, studies of climate change in the U.S. identify an array of impacts on human health, on the productivity of human and natural systems, and on human settlements. Many of these impacts are likely to be linked to human welfare. To examine the impacts of climate variability and change on human welfare, this chapter reports on two relevant bodies of literature: approaches to welfare that rely on qualitative assessment and quantitative measures, and the economic approach which monetizes, or places money values, on quantitative impacts.

The remainder of this introductory chapter is designed to provide the reader with an overview of the current state of knowledge regarding

(1) likely changes in climate and climate variability in the United States along with

(2) a general discussion of population trends, migration patterns, and the distribution of population across settlements in the U.S.

1.2 Climate Variability and Change in the United States: Context for an Assessment of Impacts on Human Systems

In the following chapters, the authors examine the likely impacts on human society of global change, especially the impacts of climate variability and change. The impact assessments in Chapters 3-5 do not rely on specific emissions and/or climate change scenarios but, instead, refer to widely-held scientific understanding of climate change and its impacts on social systems and human health and well-being in the United States. This report does not make quantitative projections of specific impacts in specific locations based on specific projections of climate drivers of these impacts. Instead the report adopts a vulnerability perspective that blends a current understanding of climate change that has already occurred with changes that are likely to occur. The report points to vulnerabilities and then, where possible, points to the likely direction and range of potential climate-related impacts.

The brief overview that follows summarizes observed changes in the global climate reported in *The Summary for Policy Makers* as part of the Intergovernmental Panel on Climate Change Fourth Assessment Report (Alley, R. et al. 2007). This introduction is intended for readers who would benefit from a short discussion of climate change as a context for the following chapters on impacts and adaptation. The general findings of the Fourth Assessment include the following observations:

- "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperature, widespread melting of snow and ice, and rising global average see level."
- "Eleven of the last twelve years rank among the 12 warmest years in the instrumental record of global surface temperatures."
- "Urban heat island effects are real but local."
- "Average temperature of the global ocean has increased to depths of at least 3000 m with warming that causes sea water to expand, contributing to sea level rise."
- "Mountain glaciers and snow cover have declined on average in both hemispheres."
- "The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapor."
- "Widespread changes in extreme temperatures have been observed over the last 50 years, with hot days, hot nights, and heat waves becoming more frequent."
- "There is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970 (Alley, R. et al. 2007)"

In addition to the projected changes described in the IPCC *Summary for Policy Makers* (Alley, R. et al. 2007), we include a brief discussion of the historical record and trends in U.S. climate for temperature means and extremes, trends in precipitation, extremes in heat and hydrology, rising sea level, and the potential for changes in the intensity of hurricanes and other catastrophic storms. Taken together, these descriptions provide a context from which to assess the likely impacts of climate variability and change on human health, human welfare, and human settlements that form the basis for Chapters 2-4.

Rising temperatures. Climate change is already affecting the United States. According to long-term station-based observational records such as the Historical Climatology Network (Karl et al., 1990; Easterling et al., 1999; Williams et al., 2005), temperatures across the continental U.S. have been rising at a rate of 0.1oF per decade since the early 1900s. Increases in average annual temperatures over the last century now exceed 1oF (Figure 1a).

Trends in annual and seasonal precipitation. Shifting precipitation patterns have also been linked to climate change. Over the last century, annual precipitation across the continental U.S. has been increasing by an average of 0.18 inches per decade (Figure 1b). Broken down by season, winter precipitation around the coastal areas, including the West, Gulf, and Atlantic coasts, has been increasing by up to 30% while precipitation in the central part of the country (the Midwest and the Great Plains) has been decreasing by up to 20%.

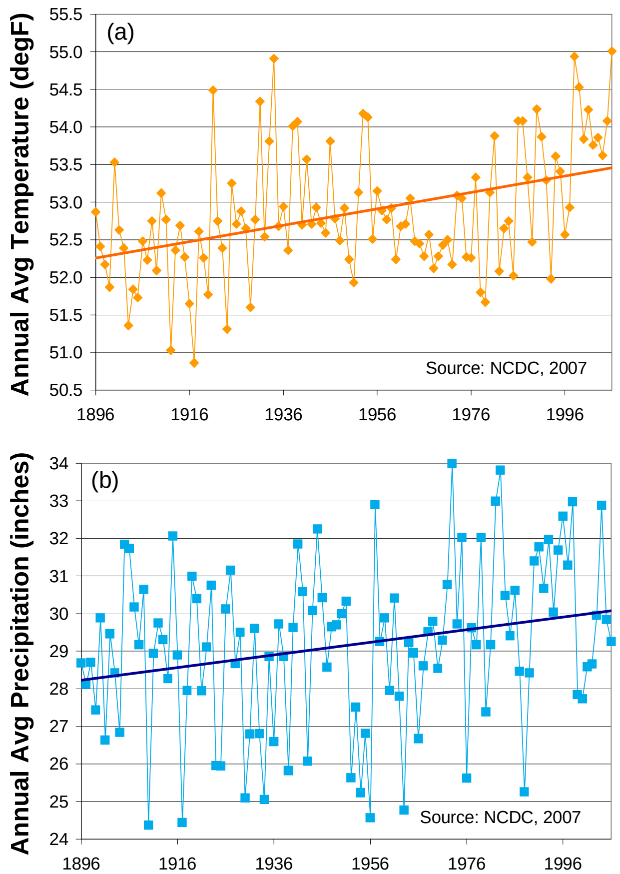


Figure 1. Observed trends in annual average (a) temperature (^{o}F) and (b) precipitation (inches) across the continental United States from 1896 to 2006 (Source: NCDC, 2007)

Large-scale spatial patterns in summer precipitation trends are more difficult to identify, as much of summer rainfall comes in the form of small-scale convective precipitation. However, it appears that there have been increases of 20-80% in summer rainfall over California and the Pacific Northwest, and decreases on the order of 20-40% across much of the south. As the Fourth Assessment Report finds, rainfall is arriving in more intense events (Alley et al., 2007).

Temperature-driven changes in extreme heat and hydrology. According to the latest IPCC findings (Alley et al., 2007), warming temperatures are already causing widespread changes in many aspects of the climate system. Prolonged heat waves are becoming more intense and lasting longer, both here in the U.S. and around the world (Frich et al., 2002).

Warmer temperatures are also melting mountain glaciers, with Glacier National Park projected to be glacier-free as early as 2030 (Hall & Fagre, 2003). More winter precipitation in northern states is falling as rain instead of snow (Huntington et al., 2004). Snow pack is also melting faster, affecting stream flow in rivers. Over the last fifty years, changes in the timing of snow melt has shifted the schedule of snow-fed stream flow in the western part of the country by 1-4 weeks earlier in the year (Stewart et al., 2005). The seasonal "center of stream flow volume" (i.e., the date at which half of the expected winter-spring stream flow has occurred) also appears to be advancing by on average 1 day per decade for streams in the Northeast (Huntington et al., 2003).

Rising sea levels and Atlantic storm intensity. Sea levels are rising at an increasing rate. The main cause for observed sea level rise over the past century is the fact that the oceans are absorbing about 80% of the additional heat being trapped in the earth-atmosphere system by greenhouse gases. This trapped heat is causing the ocean waters to expand, raising sea levels around the world. Over the first part of the century, sea level was rising at a rate of just 0.7 inches per decade (1.7 mm/yr). Over the last few decades, however, sea level has been rising nearly twice as fast, at 1.2 inches per decade (3.1 mm/yr; Alley et al., 2007). Some of this recent increase may be due to the observed acceleration in the rate of Greenland ice melting over the past decade (Rignot, 2006).

Even by themselves, rising sea levels will exacerbate the impacts of coastal storms. However, the intensity of Atlantic hurricanes and tropical cyclones has also been increasing over the last few decades. According to the IPCC, increased intensity is "as likely as not" due at least in part to warming sea surface temperatures (Emanuel, 2005; Webster et al., 2005; Alley et al., 2007). The combination of higher sea levels with more intense storms further raises the risk of serious climate change impacts on coastal zones.

Extremes. Although no single extreme event can be directly attributed to climate change, many events typical of what it is likely we can expect in the future (Alley et al., 2007) have occurred in recent decades. These include the very warm summers and prolonged heat waves of 1988, 1995, 1998, 1999 and 2006 (Karl and Knight, 1997; Ross & Lott, 1999; Stott, 2004; Meehl & Tebaldi, 2004). These heat waves affected air quality and led to significant increases in heat-related morbidity and mortality, particularly in urban areas (Semenza et al., 1996; Whitman et al., 1997). They also led to billions of dollars in agricultural losses (Ross & Lott, 1999).

Extreme events typical of what may be expected in the future also include the numerous periods of heavy downpours that have led to documented increases in flood-related losses across the continental U.S. (Chagnon, 2003). In general, more rain is falling during heavy rainfall events, and these have increased in frequency by as much as 100% across much of the Midwest and Northeast over the last century (Kunkel et al., 1999).

Finally, the intense hurricanes that battered the Gulf Coast in 2005 cannot be directly attributed to climate change alone. However, the likelihood of stronger storms appears to have increased over the past few decades (Emanuel, 2005). Furthermore, these events are certainly indicative of what may be expected in the future under higher sea levels combined with equally or even more intense storms (Knutson & Tuleya, 2004). Together, the heat waves, heavy downpours and flooding, and coastal storms experienced in recent years give us a foretaste of what we might expect to see in the future due to climate change.

1.3 Population Trends, Migration Patterns, and Development of the Nation's Landscape: A Context for Assessing Climate-related Impacts

Just as the preceding discussion of climate variability and change provides a framework for understanding impacts on human health, settlements and welfare, an overview of population trends and settlement patterns provides the basis for assessing broader interactions of global change, especially climate change, within the larger social context . Underlying many of the studies discussed in this report are assumptions about U.S. population projections across the next 20, 50 or 100 years. At the intersection of the impacts of climate variability and change, are impacts associated with demographic factors and region-specific effects. The results of impacts or risks assessments are shaped by questions such as:

- *Which coastal counties will grow most rapidly?*
- *How many more people do we expect to move into arid states in the Mountain West?*
- *What level of international immigration can we expect and which communities will be the primary gateway destinations?*
- *Which currently rural counties will become urban?*
- *What share of retirees will migrate and where will they move?*

Detailed assessments of climate-related risk make assumptions about the size and distribution of the U.S. population. These baseline projections can be done at three basic levels: 1) across the fifty states, 2) within states and regions, and 3) within cities and neighborhoods.

Given the technical and computational challenges of downscaling model-based climate change projections, quantitative impact studies tend not to address impacts at the city and neighborhood scale. This is a critical gap in the existing literature since many impacts such as: heat related deaths, exposure to vector borne disease, storm damage to uninsured property and heat induced changes in air quality do vary at this scale (Borrell et al., 2006, Patz et al., 2005, Naughton et al., 2002, McGeehin and Mirabelli 2001). This variation may be important, because vulnerable populations, like seniors, low income families, and others with more limited access to health care and property insurance who are already disproportionately impacted by climate variability and change, are often concentrated in particular urban neighborhoods. Better understanding of climate change at the community scale would provide a basis for adaptation research that addresses environmental justice / equity concerns (Rosenthal and Brandt-Rauf 2006, Bernard and McGeehin 2004).

While precise population forecasts are not feasible over long time frames, many rigorous scenarios have been developed at the national, state and regional scale. The scenarios typically provide a benchmark future for the assessments of climate change impacts. At the state level, the Census Bureau regularly produces 25-year predictions. Most states also produce county level forecasts consistent with the Census projections. While some impact studies have relied on these official population estimates, others have employed economic or land allocation models to develop independent baseline scenarios.

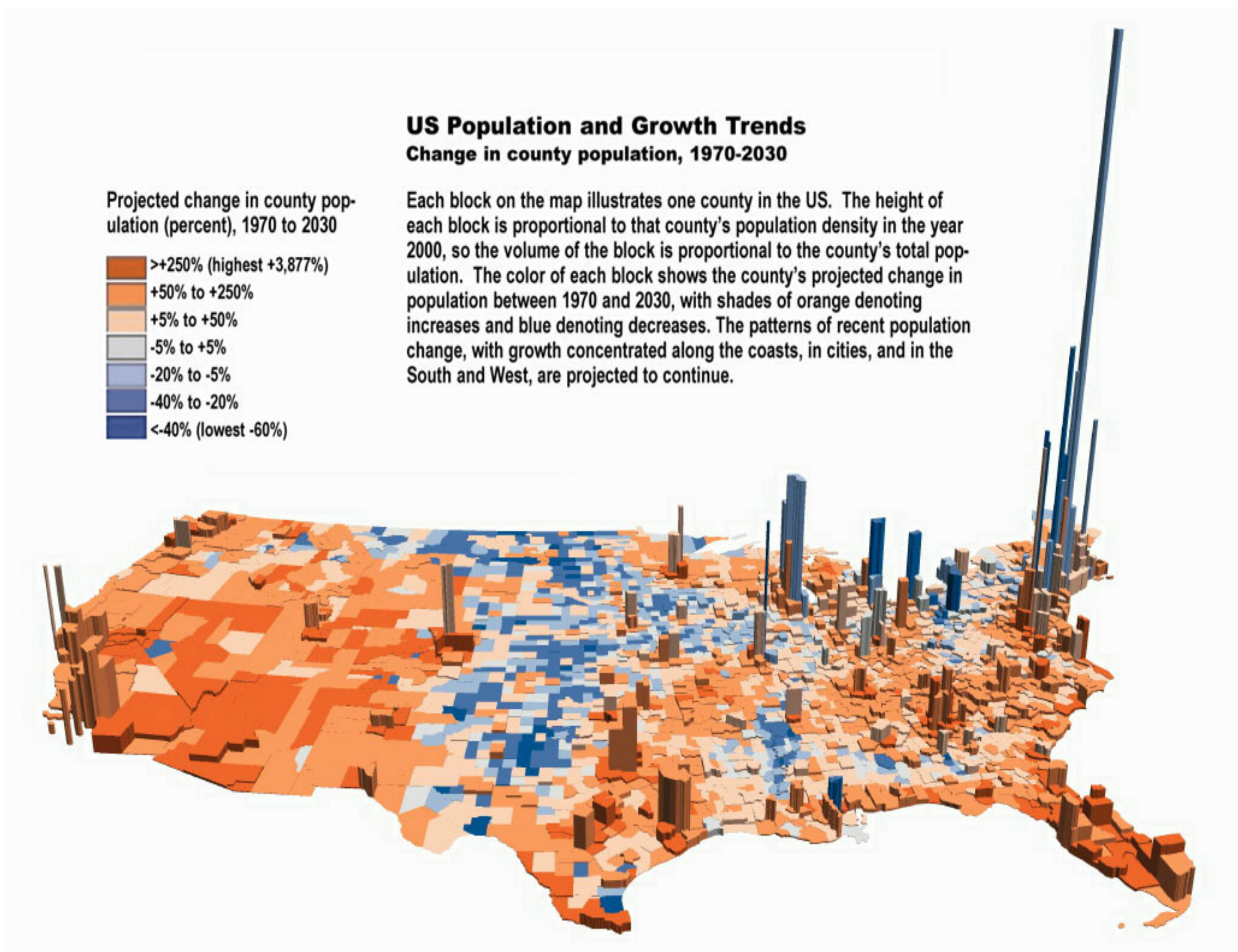


Figure 1.1: U.S. Population and Growth Trends with evidence of more pronounced growth projected along the coasts, in urban centers, and in cities in the South and West (NAST, 2001).

Although numbers produced by population forecasts are important, the striking relationship between the most likely impacts of climate change and the most likely future settlement patterns is the critical insight. *In particular, nearly all trends and forecasts point to more Americans living in areas most vulnerable to the effects of climate change.* For example, many rapidly growing places in the Mountain West are also most likely to experience decreased snow pack during winter and earlier spring melting of what snow pack there is, leading to lower stream flows, particularly during the high-demand period of summer. The most rapidly growing coastal counties also tend to be in areas most prone to hurricane activity and to storm surge. With continued growth in these vulnerable regions, research is needed to consider alternative growth futures and to minimize the vulnerability of new development, to insure that communities adopt measures to manage significant changes in sea level, temperature, rainfall and extreme weather events.

National Population Trends

- Since 1980 the U.S. population has grown by more than 40 million
- However, the growth has been unevenly distributed
  - More than 500 counties actually lost population
    - Over 2 million fewer people live in these areas
  - While just 40 counties accounted for more than half the growth (either from migration or natural increase)
    - Ranging from 2.5 million in Los Angeles County to just over 200,000 in Polk County, Florida.
- Over the next 25 years the U.S. is expected grow by more than 60 million
  - 7 states are expected to account for more than two-thirds of this growth (Florida, Texas, California, Arizona, North Carolina, Georgia, and Washington)
  - Large urban and coastal counties will continue to account for the majority of growth, although many rural and urban fringe counties will grow rapidly in percentage terms.

Source: US Census Bureau, 2005

Movement toward coastal areas has been one of the most pronounced trends over the past few decades and the trend is expected to continue. The overlay of this migration pattern with climate change forecasts has several implications. Perhaps the most obvious is the increased exposure of people and property to the effects of sea level rise and hurricanes. With rapidly growing communities near coastlines, property damages would be expected to increase even without any changes in storm frequency or intensity. If sea level rise intensifies storm surges and extreme weather events become more frequent, the negative impacts and adaptation challenges will be compounded by intensely-developed coastal zones.

The continued growth of arid states in the West is another critical crossroads for human settlements and climate change. Eleven states have significant reservoir capacity that would most likely be impacted by a significant change in precipitation and snowfall (see figure). These states are also expected to account for one-third of all U.S. population growth over the next 25 years (US Census Bureau, 2005). This dual challenge of decreased water supply in the face of rising demand is yet another example of a critical pressure point between population trends and climate change projections. For example, a study commissioned by the California Energy Commission estimated that the Sierra Mountain snow pack could be reduced by 12 to 47% by 2050 (Cayan et al 2006). At the same time, State projections anticipate an additional 20 million Californians by that date (California Department of Finance 2004). States in the Northeast and Midwest will most likely continue to see substantial out-migration to the South and West.

However, immigration from abroad and natural population increase are expected to generate some amount of population growth in nearly all states.

Within regions, two competing trends have emerged. Over the past century, advances in transportation technology – electric streetcars, freight trucks, personal automobiles, and the interstate highway system -have fueled the decentralization of urban regions (Hanson and Giuliano 2004, Garreau 1991, Lang 2003). While the Internet and telecommunications technology have contributed to this trend, they have also made central cities more important engines of economic growth (Graham and Marvin 1996, Castells 1996, Sassen 2002). Not surprisingly, most of these global cities – New York, Miami, Los Angeles, San Francisco and Seattle - are also in coastal regions. Historically, gateway cities have often been port cities, with a history of development based on easy access for immigrant populations and for international trade. During the 1990's, most large central cities experienced population growth, reversing long-standing trends.

Overall, the rate of land development at a national level has been fairly consistent over the past 20 years. However, across the 50 states, the acres of land developed for every additional person varies from less than a quarter acre per person in California and Hawaii to more than an acre per additional person in 16 states. In other words, some regions have grown rapidly with relatively modest increases in developed land, while other regions have increased the amount of developed land in spite of declining populations (NRCS 2007). The potential for regional land use policy to affect climate change impacts and adaptation opportunities seems clear. Metropolitan areas concentrate climate impacts on densely-populated urban areas that in turn multiply the climate effects in these heavily-developed business centers.

Another trend of significance for climate change is the suburbanization of poverty. A recent study noted that by 2005 the number of low income households living in suburban communities had for the first time surpassed the number living in central cities (Berube and Kneebone 2006). Although the poverty rate in cities was still double the suburban rate, there were 1 million more people overall living in poverty in America's suburbs.

Therefore, many of these people who will be more vulnerable to the effects of climate change live in older inner-ring suburbs developed in the 1950's and 60's. The climate adaptation challenge for these places is captured succinctly by a recent policy study focusing on the broader set of public policy issues in such places:

> *"Neither fully urban nor completely suburban, America's older, inner-ring, "first" suburbs have a unique set of challenges—such as concentrations of elderly and immigrant populations as well as outmoded housing and commercial buildings—very different from those of the center city and fast growing newer places. Yet first suburbs exist in a policy blind spot with little in the way of state or federal tools to help them adapt to their new realities." (Puentes and Warren 2006)*

It is often said that Americans are a nation of movers and data collected for both the 1990 and 2000 Census support this notion. While roughly half of the U.S. population had lived in the same house for the previous five years, nearly 10 percent had recently moved from out of state

(Census 1990 STF 3 Table P043 and Census 2000 STF 3 Table P24). In other words, during the five year period preceding each Census, over 20 million Americans had moved across state lines and half of those moved to an entirely different region.

Although many forces shape domestic migration, climate is a key element of perceived quality of life. In turn, quality of life can be an important factor driving the relocation decisions of households and businesses. The popularity of the Places Rated Almanac and other publications ranking cities' livability illustrates the concept's importance. Additionally, many of the indicators in these reports are based directly on climatic conditions (average winter and summer temperature, precipitation, days of sunshine, humidity, etc.).

A range of studies have attempted to quantify how natural amenities, including a favorable climate, affect migration. While the methods have varied [1] the basic conclusions are similar. In general:

- People move for a variety of reasons other than climate: proximity to family and friends, employment opportunities, lower cost of living
- Therefore, areas with natural amenities that are close to urban centers have attracted the largest numbers of in-migrants (Serow 2001)
- Climate's impact on migration varies by income with lower income groups also moving to colder areas in which their wages are likely to compare more favorably to the cost of living (Rebhun and Raveh 2006)
- For retirees, weather is a far more important rationale cited for moving out of an area than moving to an area (AARP 2006)
- Population growth in rural counties is strongly related to a more favorable climate and other key natural amenities (McGranahan 1999)

Of particular interest are the trends among rural counties. One study identified 277 rural counties as retiree destinations, with 90 emerging as new retiree destinations in the 1990's (McGranahan 2003).[2] An overwhelming share had natural amenities that would place them among the most desirable places to live.(see figure below)[3] Studies of rapidly growing "amenity counties" suggest that jobs are increasingly following the migration of working age adults to such places (Carruthers and Vias 2005, Cromartie 1998). The obvious question for climate research is: *If some regions become less frigid in the winter and others more hot and humid in the summer, will these migration patterns change substantially?*

[1] Study methodologies include: aggregate studies of population changes alongside regional characteristics, explanatory models developed from individual migration data and individual surveys.

[2] Defined by the authors as a greater than 15% increase in the over 60 population in the previous decade.

[3] Researchers at the USDA Economic Research Service ranked counties according to a natural amenity index (average winter and summer temperature, winter sunshine, summer humidity, water area and topography)

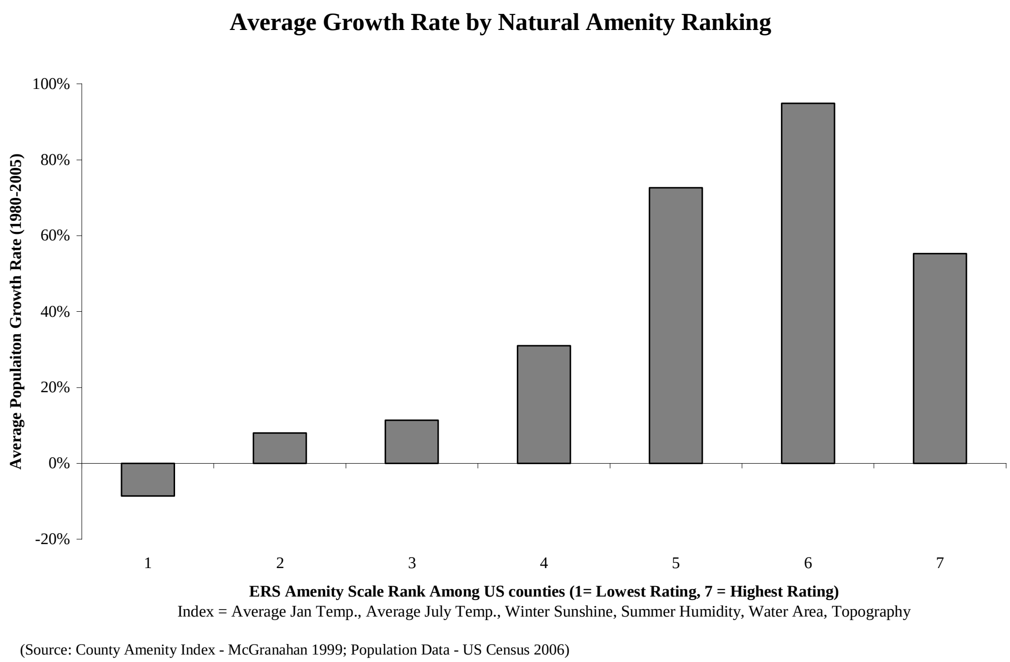


Figure 1.2. Average population growth rate by Natural Amenity Index. (1980-2005). High amenity indices (based on county-level data) correlate with high population growth.

1.4 Reporting Uncertainty in SAP 4.6

We have adopted a framework for treating uncertainty in this report that is informed by ongoing discussion within the Climate Change Science Program. General guidance issued by the CCSP on handling uncertainty in the various Synthesis and Assessment Products (SAPs), draws on best practices documented in previous large assessment exercises, such as the Intergovernmental Panel on Climate Change (IPCC), as well as on new CCSP efforts. The specific application of this guidance in each SAP is a function of the subject matter and scope of the particular report.

In this report, as in the other SAPs, handling uncertainty involves characterization (of the uncertainty surrounding a finding, judgment, or prediction) and communication (of this uncertainty) in clear, precise, objective language. This characterization and communication in this report reflects the following guiding principles:

- It is important to recognize the basic differences between descriptions of uncertainty in terms of *likelihood* or in terms of *level of confidence* of the science. Likelihood is relevant when assessing the chance of defined future occurrence or outcome, often expressed in a probabilistic way. Level of confidence refers to the degree of belief in the scientific community that available understanding, models, and analyses are accurate, expressed by the degree of consensus in the available evidence and its interpretation. Both are important when dealing with climate change impacts assessments and both must be communicated.

Specifically:

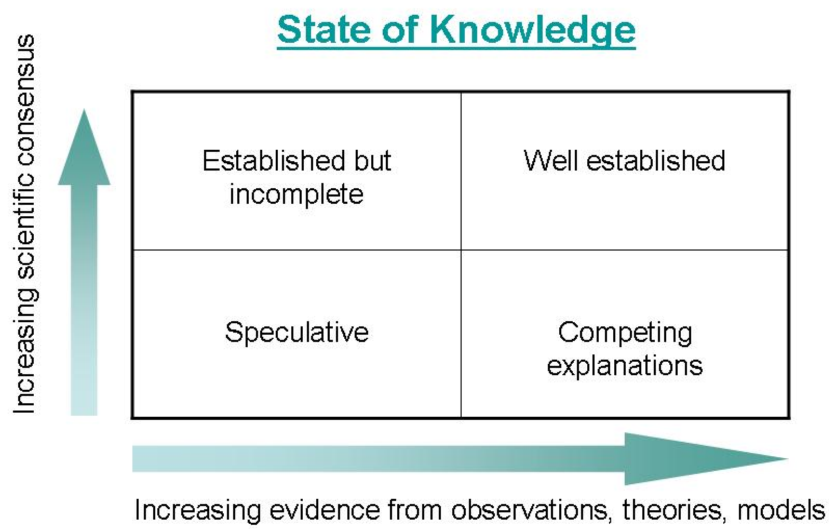
- When expressing likelihood, there are many words used to describe different degrees of uncertainty: e.g., “probable,” “possible,” “likely,” “unlikely,” etc. Such qualitative language is inadequate because the same words can mean very different things to different people, and the same words can mean very different things to the same person in different contexts. Therefore, in this report, numerical probabilities are assigned to such qualifiers (Table 1), which are then used consistently throughout the report.

Table 1. Defining the likelihood of an outcome where it can be estimated probabilistically.

Likelihood Terminology	Likelihood of the occurrence / outcome
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 - 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

- When dealing with the level of confidence in our scientific judgments about climate change and its impacts, it is important to consider two attributes: the amount of evidence available to support the judgment being made and the degree of consensus within the scientific community about that judgment. The state of knowledge underlying any judgment can in principle be sorted into specific categories (e.g., see Figure 1).

Figure 1.3 State of Knowledge



Throughout this report, an evaluation of uncertainty will be presented to accompany any judgment, finding, or conclusion made in the text. If such a judgment, finding, or conclusion regards the subjective probability of a future event, for example a future projection of a specific climate change impact, the appropriate expression of likelihood (taken from Table 1) will be used. If instead the finding is an assessment of the degree of knowledge and understanding currently present in the scientific community about a topic, as expressed in the literature, the report will explicitly address questions like, "Is there a lot of literature out there dealing with this issue, or only a little?" and, "For the literature that does exist, is there broad agreement or wide disagreement?"

The application of this approach to likelihood and level of confidence estimates varies in each of the three core chapters (Chapters 3-5) according to the current richness of the respective knowledge bases. A relatively more extensive and specific application is possible for health impacts, only a more general approach is warranted for conclusions about human settlements and uncertainty statements about human welfare conclusions are necessarily the least explicit.

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Synthesis and Assessment Product 4.6

Chapter 2

The Human Dimensions of Global Change in the United States

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Lead Authors: Kristie L. Ebi, ESS LLC, Frances G. Sussman, Environmental Economics Consulting, Thomas J.Wilbanks, Oak Ridge National Laboratory

2.1 How is climate change likely to affect people and communities in the United States over the coming decades?

Our daily conversations often begin or end with a pronouncement about the day's weather.

"It's too nice to be working indoors."

"We need rain."

"This is the 5th 100-degree day this month."

Our focus on the day-to-day fluctuations of weather reflects the far-reaching impacts that weather has on our sense of well-being and comfort, as well as, our concern about weather extremes that have the capacity to disrupt or even end lives. Against the backdrop of the daily variations in weather, we are becoming more aware of longer-term changes in climate described in the popular press as global warming. Just as our daily experience of weather is tied to where we live and work, so too will our experience of climate variability and change. In the United States, we are beginning to observe the manifestations of a long-term warming trend.

This chapter tells the story of how climate change is likely to be experienced by Americans, both in their daily lives and in the lives of their communities. It examines how the impacts of climate change are determined by where people live and how our health and well-being is inextricably tied to multiple facets of global change. The chapter reviews how demographic patterns in the United States have evolved to create vulnerabilities to climate change and how climate's effects on human health and welfare are determined, at least in part, by the context of place. The chapter analyzes what makes communities livable and how those characteristics interact with climate. Finally, it assesses how adaptation strategies can be employed to mediate climate impacts on human health, human settlements, and individual and collective well-being.

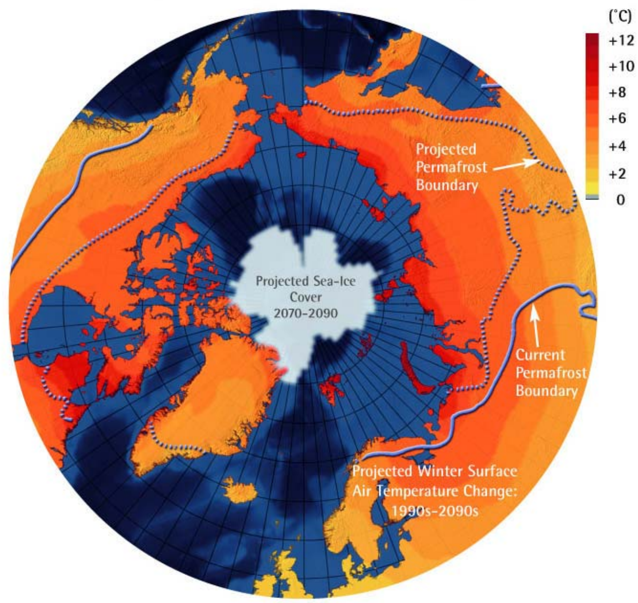
2.1.1. Projected Climate Change: The U.S. experience. [see Sections 1.2, 3.2, 4.2, 5.2]

In the United States, we are now observing the evidence of long-term changes in temperature and precipitation consistent with global warming. Projected climate change is expected to exert significant effects on individuals and communities across the country. Climate change is being realized through more intense tropical storms, permafrost thaw, heat waves, droughts, glacial retreat, early melting of snowpack, low reservoir levels, erosion of coastal zones, sea level rise, and heavy precipitation events. Climate change is also realized in indirect effects, such as the large climate-related worsening of ambient air pollution and the indirect effects of climate on disease transmission dynamics.

Tropical storms. Observations indicate that a greater number of more intense tropical storms have occurred since about 1970. If this trend continues, coastal communities along the Gulf Coast and the Southeast Atlantic are likely to experience increased disruptions. The increased risks to these communities in coastal zones and low-lying areas are related to the combination of coastal erosion, storm surge, sea level rise, and the higher peak winds and heavier precipitation associated with the increase in tropical storm intensity. Furthermore, extensive coastal development magnifies the impacts of tropical storms by putting more communities at risk of sustaining a direct hit from a hurricane or a tropical storm. While the number of intense tropical storms appears to be increasing, globally there is little trend in overall tropical storm frequency. The record of tropical storm activity prior to 1970 is of lower quality than the more recent observations, making it more difficult to confidently discern long-term trends.

Water scarcity**.** Water shortages are the legacy of a generally warmer climate with its associated decreases in snow and spring runoff from snowmelt and of increasing demands related to population growth. Coping with the consequences of decreased precipitation and increasing temperatures will require major changes in water management and allocation systems, especially in the West. Communities will be called upon to allocate scarce water resources between municipal, industrial, and agricultural uses, between human uses and those of existing ecosystems, and between maintenance of reservoirs and dams for recreation and hydroelectric production.

Arctic warming, permafrost thaw, and coastal flooding. Warming in the Arctic is leading to retreat of sea ice, especially from the northern coast of Alaska, and to coastal erosion and permafrost thaw. Coastal erosion is putting communities at risk and disrupting homes and livelihoods. Native Peoples have been disproportionately affected. Melting permafrost, coupled with storm surge along the coast which until recently was packed with sea ice, have caused entire communities to retreat from the coast. Infrastructure (including oil pipelines, roadways, and buildings) has sustained and will continue to sustain damage associated with permafrost thaw (see Box 1).



©2004, ACIA / Map ©Clifford Grabhorn

Sinkhole in permafrost near Fairbanks Alaska. Source: NCAR

Box 1 Alaska: The Permafrost Retreat

Global model simulations from the National Center of Atmospheric Research (NCAR) show that more than 50% of the topmost layer of permafrost could thaw by 2050 and as much as 90% by 2100. The study found that approximately 25% of the Northern Hemisphere land mass contains permafrost --- including an active surface layer of as little as a few centimeters to a depth of several meters. Deeper permafrost layers will remain frozen. But recent warming has degraded large sections of permafrost across central Alaska. Results of the thaw include buckled highways and airport runways, destabilized houses, commercial buildings, and pipelines, and “drunken forests” where trees begin to uproot and lean. Further degradation of the permafrost is expected to threaten migratory patterns of caribou and reindeer. Thaw will also impact natural ecosystems through lake drainage, collapse of ground surface, and development of wetlands.

National Center for Atmospheric Research. 2005. Most of Arctic’s Near-Surface Permafrost May Thaw by 2100. Geophysical Research Letters.

Arctic Climate Impact Assessment. Impacts of a Warming Arctic. 2004. SJ Hassol, editor. Cambridge University Press.

Drought and wildfire. Droughts in the West and Southeast are likely to be more persistent through the 2050s. Drought conditions not only challenge the provision of water for individual consumption, but also the requirements of agricultural and industrial uses. With severe, persistent drought, wildfires and associated displacement of at-risk populations may become more common. Dried vegetation, especially in heavily forested areas will aggravate the risk for wildfire. At the same time, increased development of communities in at-risk areas will imperil lives and properties.

Glacial retreat, snow melt, and lake levels. Climate models also project warming in the intermountain West accompanied by glacial retreat, decreased snow pack, earlier snow melt and reduced summer stream flows on rivers issuing from the snowpack. These changes are affecting rapidly-developing cities in the West and exacerbating water allocation controversies. Conflicts over western water supplies are expected to become more problematic in coming decades. Water levels have fallen dramatically in recent years in large reservoirs across the West. For instance, Lake Mead has historically provided a steady water supply for the Colorado River Basin. However, drought conditions and decreased runoff have threatened the lake's supplies. Retreat of the water in Lake Mead has forced changes in recreational activities with closing or relocation of marinas and other shoreline development. The duration of drought conditions in the Colorado River system is similar in extent to a drought experienced in the late 1950s. It is not known whether the current drought is a sentinel for drought conditions associated with longer-term climate change or whether the drought is background variability in climate conditions.

Lake Mead: As of July 7, 2003 the lake was 1129 Feet (344.1m) above sea level. Full elevation is at 1221.4 (372.3) feet above sea level, according to the Bureau of Reclamations. Photo courtesy of NASA.

Sea level rise and erosion of coastal zones. Erosion of coastal zones associated with sea level rise will be especially severe along the Gulf Coast and the Mid-Atlantic regions of the United States. Higher temperatures are expected to raise sea level by expanding ocean water, melting glaciers and causing ice sheets in Greenland and the Antarctic to melt. In the past century, global sea level rose 5-8 inches. Coupled with subsidence in these coastal areas, projections now suggest that the Gulf Coast and Mid-Atlantic will experience a one to three foot rise in relative sea level during the 21st century. Rising sea level erodes beaches and low-lying lands, increases salinity in bays and estuaries, and contributes to coastal flooding. Adaptation measures (such as replenishing beaches and constructing seawalls) could adversely affect coastal ecosystems and public access and use of beaches. Complicating concerns about sea level rise is the continuing increase in coastal zone development. Even without changes in sea level, dense coastal development is putting millions of Americans and their properties at risk.

River flooding and extreme precipitation events. There is observational evidence of increases in the number of heavy precipitation events over the past decades, particularly over land, and widespread increases in the frequency of heavy precipitation events across the United States are projected for the future. These findings are consistent with observed and projected warming and associated increases in atmospheric water vapor. In some instances, extreme precipitation events lead to localized flash flooding, in other instances, these events may lead to extensive riverine floods across entire river basins (such as that experienced in the past decade on the Red River of the North, the Sacramento River, and the Fraser River). Costly recovery efforts in the aftermath of these floods have taxed the capacity of insurers, federal, state, and local response agencies, and flood victims.

Urban heat. A large fraction of the U.S. population lives in urban areas. Increases in temperature from global warming will be compounded by increases in temperature due to local urban heat island effects, making cities more vulnerable to higher temperatures than would be expected with warming alone. Existing stresses in urban areas include traffic congestion, degraded air and water quality, and disruptions to everyday life due to decaying or failing infrastructure. Climate change is likely to influence and be influenced by these stressors. Populations of the very old, the very young, and those with preexisting cardiopulmonary conditions are expected to be affected by extreme heat coupled with degraded air quality.

Indirect effects of climate change.
Vector, water, or food-borne diseases exhibit distinct seasonal patterns that suggest *a priori* that weather and/or climate influences their distribution and incidence. Similarly, millions of Americans live in areas that fail to meet the health-based National Ambient Air Quality Standards (NAAQS) for ozone and fine particulates (PM2.5). Both ozone and PM2.5 have well-documented cardiovascular and pulmonary health effects and ambient concentrations of these pollutants have the potential to be influenced by climate change, especially high temperatures.

2.1.2. Complex linkages: the role of non-climate factors

Climate is only one of a number of global changes that affect human well-being. The major impacts of climate are shaped by interactions with non-climate factors that can modify or mediate direct climate impacts. Except in the instance of extreme events, climate variability and change in the United States are seldom the most important among multiple issues (see Table 1). The overall severity of climate impacts depends on an array of non-climate factors, including:

- demographic changes, including immigration and aging of the population;
- region-specific vulnerabilities, e.g., extensively developed coastal zones;
- the social, political, and cultural context;
- economic conditions, e.g., productivity and employment;
- available resources, e.g., budgetary and natural resources;
- available technologies;
- conditions of the built environment, e.g., age and capacity of existing infrastructure;
- land use change; and,
- the availability and quality of public health and social services infrastructure.

Because of joint or multiple paths of causation, assessing climate change impacts requires assumptions about a range of socioeconomic futures. The past half-century has seen sustained economic growth in the United States, stunning levels of technological advancement, and population growth that has concentrated people in urban, coastal and arid settings. There has been overall movement toward the South and West and we have seen shifts of population from frost-belt to sun-belt and the movement of households from urban centers to far flung suburbs. In the United States, population growth in coastal zones magnifies the impacts of climate variability and change just as inadequate storm-drainage infrastructure can aggravate climate impacts in flood-prone areas. In addition, rapid development of new information technologies, such as the internet, and declining costs of airline travel have made previously remote locations more accessible for work, recreation, or retirement. Collectively, these developments indicate the need for socioeconomic scenarios as a mechanism for better characterizing the complex linkages between climate and non-climate factors.

The same social and economic systems that bear the stress of climate change also bear the stress of air and water pollution, the influx of immigrants, and over-burdened infrastructure in rapidly-growing metropolitan centers and coastal zones. While non-climate stressors are currently more pronounced than climate impacts, one cannot assume that this trend will persist. Understanding the impacts of climate change and variability on health and quality of life assumes knowledge of how these dynamics might vary by location and across time and socioeconomic group. The effects of climate change often spread from directly affected areas and sectors to other areas and sectors through complex linkages. The relative importance of climate change depends on the directness of each climate impact and on demographic, social, economic, institutional, and political factors, including, the degree of preparedness.

Consider the wide swath of damage left by Hurricanes Katrina and Rita in 2005. Damage was measured not only in terms of lives and property lost, but also in terms of the devastating impacts on infrastructure, neighborhoods, businesses, schools, and hospitals as well as in the disruption to families and friends in established communities, with lost livelihoods, challenges to psychological well-being, and exacerbation of chronic illnesses. While the aftermath of a single hurricane is not the measure of climate change, such an event demonstrates the disruptive power of climate impacts and paints a picture of the resulting tangle of climate and non-climate stressors that complicate and challenge efforts to respond and to adapt.

TABLE 1: Current and projected climate change impacts and interaction with non-climate stressors. Source: Revised from the IPCC Working Group II, Fourth Assessment Report, Technical Summary, 2007.				
Climate driven phenomenon	Evidence of current impact / vulnerability	Non-climate stressors	Projected future impact / vulnerability	Regions / Populations Affected
Changes in extreme conditions				
Tropical cyclones / storm surge	Flood and wind damages; economic losses; transportation, infrastructure and tourism losses	Land use Population density Flood defenses Institutional capacities, e.g., emergency preparedness & public health response	Increased vulnerability in storm prone coastal zones; effects on settlements, health, tourism, economic and transportation systems; buildings & infrastructure	Gulf Coast; Southeast Atlantic Coast; Pacific Coast; Alaska Coast
Extreme rainfall / riverine floods	Erosion / landslide; land flooding; impacts to settlements, transportation systems, and infrastructure	Storm drainage infrastructure; river levee systems; flood plain containment	Increased vulnerability in storm prone coastal zones; effects on settlements, health, tourism, economic and transportation systems; buildings & infrastructure	Out-of-bank river floods especially in Midwest and Great Plains
Heat or cold waves	Effects on human health; requirements for energy, water and other services; infrastructure impacts (especially energy and transportation	Building design Interior temperature control Social contexts Institutional capacities	Increased vulnerabilities in some regions and among some populations; health effects; changes in energy requirements	Mid-latitude regions; Very old and very young; Seniors and disabled living alone
Drought	Water availability; livelihoods; energy generation; migration; transportation in water bodies; wild fires	Water systems; competing water uses; energy demand; water demand constraints; draw down of existing reservoir systems	Water resource challenges in affected areas; shifts in locations of population and economic activities; additional investments in municipal and agricultural water supplies; wild fires	Semi-arid and arid regions, e.g. the Intermountain West and the desert Southwest and the Southeast
Changes in average conditions				
Temperature	Energy demands and costs; urban air quality; permafrost thaw; tourism and recreation; retail consumption; livelihoods; loss of melt water	Demographic and economic changes; land use changes; technological innovations; air pollution; institutional capacities	Shifts in energy demand; worsening of air quality; impacts on settlements and livelihoods depending on melt water; threats to settlements and infrastructure from thawing permafrost	Diverse populations, including very young and very old; those without air conditioning; outdoor workers and outdoor recreation
Precipitation	Agricultural livelihoods, saline intrusion, tourism, water infrastructures, tourism; energy supplies	Competition from other regions and sectors; water resource allocations	Depending on the region, vulnerabilities in some areas to effects of precipitation increases (flooding) and decreases (drought)	Poor populations; poor regions; flood zone residents
Sea level rise	Coastal land uses; flood risk; water logging; water infrastructures	Trends in coastal development, settlements, and land uses	Long-term increases in vulnerabilities of low-lying coastal areas	Coastal zones; Poor populations; poor regions

2.1.3. Brief summary of the impacts of climate change on human well-being in the United States [see Sections 3.2, 3.3, 4.2, 5.3 of this report]

Climate change impacts in the United States are characterized at varying degrees of certainty. This section provides a brief overview of potential impacts of climate change on human health, human settlements, and human welfare. It includes tables describing the relative likelihood associated with important endpoints in each focus area.

Impacts on human health. The health and well-being of millions of Americans are tied to climate-related exposures to:

- extreme heat
- vector-borne disease
- water-borne disease
- injuries associated with flooding and dangerous storms, and
- cardiopulmonary illnesses aggravated by the interaction of air pollutants (especially ground level ozone) and warmer temperatures.

Northeastern and Midwestern cities experience severe heat waves with adverse health impacts, especially among the elderly or the poor who cannot afford to air condition their homes. Urban heat island effects are real but local. Cities are and will continue to be challenged by the increased number, intensity, and duration of heat waves.

The central message is two-fold. First, health impacts of climate on communities in the United States are likely to be protected by the response capacity of public health and medical care systems. It is widely believed that the health and human service infrastructure in the United States has and will continue to be able to address and contain most health impacts. But, this supposition means that timely, effective adaptation measures will be developed and deployed. We have already seen serious failures of medical and emergency relief systems in the aftermath of Hurricanes Katrina and Rita, so we must conclude that adaptation to human health impacts will require extensive coordination and an ongoing commitment to capacity building in the public health sector (see Box 2). Table 2.XX summarizes a number of human health impacts and their associated likelihood. Note: the characterization of likelihood is described in Chapter 1, Section 1.4.

Table 2.1 Likelihood of Climate Change Impacts on Human Health

Description of Effects	Likelihood
Contributes to current morbidity and premature mortality in the U.S.	More likely than not
Climate-related health impacts will increase over the coming decades.	Very likely
Climate change will seldom be the primary factor affecting the burden of climate-related injuries, illness, and death in a population. Timely and effective adaptation can reduce some projected impacts.	Virtually certain
Climate change will have negative and positive health impacts in the U.S.	Very likely
Morbidity and mortality due to floods, droughts, windstorms, and wildfires will increase with climate change	Likely
Morbidity and mortality will increase due to projected increases in the frequency and intensity of heatwaves and will decrease due to projected decreases in the frequency and intensity of cold spells.	Very likely
The geographic distribution and length of the transmission season of some vector-borne and zoonotic diseases will alter in response to climate change with both increases and decreases.	Very likely
Climate change will increase outbreaks of waterborne diseases	Very likely
Climate change will increase health outcomes related to air pollution	Likely
Populations particularly vulnerable to climate change include older adults, infants, and children, the poor and marginalized, individuals with certain chronic medical conditions, and certain occupational groups	Virtually certain

Table 2.1 Likelihood of Climate Change Impacts on Human Health

Description of Effects	Likelihood
Although the U.S. has high capacity to cope with the projected health impacts of climate change there is a need to strengthen programs and activities aimed at reducing the risks of climate-sensitive health determinants and outcomes	Virtually certain
Additional research is needed to better understand possible climate-related impacts in the context of all key factors that affect health outcomes and reduce uncertainties	Virtually certain

New Orleans in the aftermath of Hurricane Katrina, 2007. Photos: American Red Cross and NOAA.

Box 2. Mental health devastation in hurricane's wake

In the aftermath of Hurricane Katrina, mental health services in New Orleans have been challenged by increased incidence of serious mental illness, including anxiety, major depression, and post-traumatic stress disorder (PTSD). Just as the need for mental health care soars, the facilities and providers available for patient care have plummeted. Barbee, et al. reports in *Time Magazine* (August 1, 2006) about his recent article in the *Journal of the American Medical Association* (JAMA) that "the event is still unfolding. People are losing jobs. They are moving because they are so discouraged by the situation. There is a lot of uncertainty about the future. It is not easy to live here."

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 fewer than 2% were getting professional attention. Troubling also are statistics on suicide, which evidence an increase of 25% in the post-Katrina suicide rate. Barbee cautions that this is likely a low estimate, given that suicide is typically under-reported.

Barbee also reports that psychiatric hospital beds number fewer than 20 in New Orleans, just as the number of psychiatrists available to see patients in the Crescent City has fallen from 196 to as few as 22. Charity Hospital, the teaching hospital for Louisiana State University Medical School has not reopened its 96 psychiatric beds and it is likely that Charity will remain shuttered because of the overwhelming damage from post-Katrina flooding.

Impacts on human settlements. Human settlements are expected to be impacted by climate change in a variety of ways, including:

- Increased energy demand associated with extreme temperatures,
- Strain on municipal, agricultural and industrial water supplies in the intermountain West and the desert Southwest,
- Disruption of infrastructure, including levee systems, river channels, bridges and highway systems, and communication systems in the aftermath of tropical storms and flooding events, and
- Disruption of communities and property loss from wildfires.

Human settlements have used "hard" approaches, such as infrastructure, and "soft" approaches, such as regulations, to protect and adapt settlements to environmental change. Examples include water supply and waste water systems, drainage networks, buildings, transportation systems, land use and zoning controls, water quality standards and emission caps, and tax incentives. The fact that both regulations and infrastructures vary considerably across the United States is an expression of related cultural, economic, and environmental factors. Mechanisms either now exist or can be anticipated to be developed to meet the challenges of climate change on human settlements. Urban design, which routinely deals with uncertainty, has the capacity to institutionalize adaptation by adapting existing mechanisms and/or developing new ones to meet the challenges of climate change on human settlements. When climate change is incorporated in the planning process, it can be addressed as yet another uncertainty.

Table 2.XX summarizes a number of human settlement impacts and their associated likelihood.

Table 2.2 Likelihood of Climate Change Impacts on Human Settlements

Description of Effects	Likelihood
Climate change will seldom be a primary factor in an area's development compared with other driving forces for development. It is likely to be a secondary factor, with its importance determined mainly by its interactions with other factors, except in the case of major abrupt climate change.	Very likely
Effects of climate change will vary considerably according to location-specific vulnerabilities, and the most vulnerable areas are likely to be Alaska, coastal and river basin locations susceptible to flooding, arid areas where water scarcity is a pressing issue, and areas whose economic bases are climate-sensitive.	Very likely
Except for Alaska, the main impact concerns have to do with changes in the intensity, frequency and/or location of extreme weather events and, in some cases, water availability rather than changes in temperature.	Very likely
Potentials for adaptation through technological and institutional development as well as behavioral changes are considerable, especially where such developments meet other sustainable development needs.	Extremely likely
While uncertainties are very large about specific impacts in specific time periods, it is possible to talk with a higher level of confidence about **vulnerabilities** to impacts for most settlements in most parts of the U.S.	Virtually certain
Clarifying these vulnerabilities and reducing uncertainties about impacts would benefit from a higher level of effort in impact research	Virtually certain
Promoting climate change mitigation and adaptation discussions at an urban scale will benefit from involvement of stakeholders	Virtually certain

Source: Reuters News Service.Telegraph UK, 2001. http://www.telegraph.co.uk/news/main.jhtml?xml=/news/2007/03/12/nfire12.xml

BOX 3. Multiple stressors. Wildfire and the degradation of air quality

Californians currently experience the worst air quality in the nation. More than 90 percent of the population lives in areas that violate air quality standards for either tropospheric ozone or airborne particulate matter. These pollutants can cause or aggravate a wide range of health problems including asthma and other acute respiratory and cardiovascular diseases, and can decrease lung function in children. Combined, ozone and particulate matter contribute to as many as 8,800 deaths and $71 billion in healthcare costs every year in California. If global background ozone levels increase as projected in some climate change scenarios, it may become impossible to meet local air quality standards. Higher temperatures are expected to increase the frequency, duration, and intensity of conditions conducive to air pollution formation. If temperatures rise to the medium warming range, there will be 75 to 85 percent more days with weather conducive to ozone formation in Los Angeles and the San Joaquin Valley, relative to today's conditions. Air quality could be further compromised by increases in wildfires, which emit fine particulate matter that can travel long distances depending on wind conditions. The most recent analysis suggests that if heat-trapping gas emissions are not significantly reduced, large wildfires could become up to 55 percent more frequent toward the end of the century.

Source: Our Changing Climate: Assessing the Risks to California. 2003. A Summary Report from the California Climate Change Center.

Impacts on human welfare. Climate change impacts on human welfare is expected to include a range of effects, such as:

- Disruption of recreation and outdoor activities due to extreme temperatures,
- Limit on some snow-related recreational activities,
- Reduced job opportunities in areas dependent on natural resources, such as agricultural production and the tourism industry,
- Higher electricity prices resulting from increased demand for air conditioning, and
- Erosion of recreational beaches by sea level rise.

The goal of successful adaptation to climate impacts is to maintain the long-term sustainability and survival of communities. Given their control over shared resources, communities have the capacity to adapt to climate change in larger and more coordinated ways than individuals, by creating plans and strategies to increase resilience in the face of future shocks. At the same time ensuring that the negative impacts of climate change do not fall disproportionately on the most vulnerable populations.

Table 2.3 Likelihood of Climate Change Impacts on Human Welfare	
Description of Effects	Likelihood
Human welfare is a multi-dimensional concept, and the effects of climate change on welfare depend on interdependencies in human and natural systems.	Virtually certain
Climate change will have positive and negative non-market effects on health, recreation, amenities, and communities	Very likely
Ecosystem changes that have already been detected or predicted within this century will have negative effects on some of the services provided by ecosystems, such as air and water quality regulation, crop pollination, or support services such as photosynthesis	Likely
Additional research is needed to understand how climate impacts communities, and how communities are vulnerable (or can b made more resilient) in the face of climate change	Very likely
Additional research is needed to understand the linkages between the effects of climate change on individual sectors and the non-market goods and services valued by humans	Very likely

2.2 What does climate change mean for most Americans? [see Section 1.3]

2.2.1. Some Americans may experience only marginal impacts of climate change.

Given the relative wealth of citizens in the United States, we expect that Americans will generally be less vulnerable to climate change than populations in less developed nations world-wide. We expect increased coping capacity to be associated with greater wealth, such that within the next 50 years, the middle class and the affluent in the United States could remain largely unaffected by climate change. Nevertheless, significant numbers of Americans will be affected by the impacts of climate. Among those who own property in vulnerable regions, wealth alone will not spare them from sustaining costly losses to homes and personal possessions. Economic well-being does not protect individual welfare during severe storm events, flooding, and heat waves. In addition, we have observed that monetary damages associated with weather extremes have markedly increased in recent decades, and that trend is expected to continue. In particular, densely-developed coastal zones have experienced and will continue to experience disproportionate climate-related impacts.

In the international arena, the United States might incur significant burdens related to the impacts of climate change in nations and among peoples who are less able to adapt. For instance, the United States might become the destination for immigrants whose countries of origin suffer drought conditions that severely compromise water supplies, disrupt homes and businesses, cut agricultural production and lead to social unrest. An influx of climate refugees is likely to be most pronounced from areas where rivers form international boundaries and where there are multiple, competing claimants on dwindling water supplies. Similarly, immigrants might arrive from low-lying coastal nations and island nations where sea level rise is expected to cause extensive coastal flooding and associated salt water intrusion into agricultural lands rendering thousands of square kilometers permanently uninhabitable or unproductive. Finally, immigrants to the United States may be more likely to introduce infectious diseases not already prevalent in this country.

2.2.2. However, some Americans, in some locations, will be vulnerable to climate change.

The changes in climate that matter most to people include direct physical impacts and indirect effects such as those on health; income and employment; the availability and price of goods and services; property values; recreational opportunities; the character of the landscape; and the political, social and economic aspects of communities. Climate and non-climate changes are experienced by people where they live, work, and play. Place is a realization of historical development decisions and of patterns of economic growth and elements of social change. This section describes the relative vulnerability of populations, both in terms of individuals and of communities.

Vulnerable people. Conventional wisdom is that climate change is expected to disproportionately affect vulnerable people in vulnerable places: For instance, impacts of extreme heat on human health are concentrated among the poor, the very young, and the elderly living in homes without air conditioning. Likewise, human health impacts are associated with degraded air quality and are concentrated among patients with existing cardiopulmonary conditions. Similarly, the poor in vulnerable locations are at greater risk to climate change as they tend to have limited capacity for adaptation.

The poor, the elderly, the disabled, and those who live alone are most vulnerable to climate change. In the event of evacuations of low-lying areas during tropical storms, those who stay behind either by choice or by the dictates of circumstance will be vulnerable – for their safety, their well-being, and their property – to extreme wind and rain, storm surge and coastal flooding. It is assumed that the property and life lost associated with extreme events will be concentrated among people with limited capacity to mount an effective response, such as evacuating at-risk locations. There is evidence, however, that many people choose to accept the risk rather than respond to public safety advisories. Some who remain behind do so by choice. Further complicating the failure to evacuate is the impression that many who choose to stay may underestimate their actual risk. In other words, they accept the risks they anticipate but not necessarily the risks as they actually prevail.

Population changes have shaped patterns of vulnerability to climate. The United States population has not simply grown, it has also shifted in its makeup and distribution. For example, the 65 and older age group has increased from 1 in 25 in 1900 to 1 in 8 in 2000. Older people are physiologically more vulnerable to heat stress and air pollution. Retirees have migrated in large numbers to the South and the West. This migration pattern is only sustainable because of the nearly universal spread of air conditioning. In 1978, 23% of U.S. homes had air conditioning. By 1997, that share had increased to 47% percent with as many as 93% of homes in the South having air conditioning. (Trends in Residential Air-Conditioning Usage from 1978 to 1997. U.S. Department of Energy). Nonetheless, lives are lost each year in big cities among the elderly and otherwise vulnerable populations who succumb to extreme heat in homes without air conditioning. These deaths are nearly entirely preventable.

Vulnerable places. Places where climate change can be expected to have the most severe consequences include:
(1) urban centers with aging infrastructure and extreme heat concentrated in urban heat islands,
(2) coastal zones and riverine flood plains,
(3) water-stressed arid regions of the mountain and desert West, and
(4) Arctic areas subject to coastal storms and flooding and permafrost melt.
Even sustained economic and population growth can stress vulnerable places through pollution, congestion, and demands on land and water and other natural resources.

In 2000, the population in the United States was 291 million, including: 83.0% in metropolitan areas, 10.3% in micropolitan areas (urban centers that have a population greater than 10,000 and less than 50,000), and only 6.7% outside core statistical areas. Between 1900 and 2000, the mean center of the U.S. population moved about 324 miles to the west and 101 miles to the south. In 1900, 62% of the U.S. population lived in either the Northeast or the Midwest. By 2000, 58% of the population resided in either the South or West. The four most populous states in 2000 —

California, Texas, Florida, and New York — represented 38% of the total growth in the United States during the 20th century and shared significant vulnerability to coastal storms, severe drought, and urban heat island effects.

Population movement to arid regions and changes in water allocation will stress water supplies, especially among native peoples and in the intermountain West, desert Southwest and Great Plains. Overuse of streams and rivers in the West is common in vulnerable regions with high agricultural irrigation demands especially those along the eastern front of the Rocky Mountains in Colorado, in Southern California, and in the Central Valley of California. In forty years (from 1960 to 2000), Colorado's population grew by 245%. Rapid population and economic growth in these arid regions have dramatically increased vulnerability to water shortages.

Communities in coastal zones enjoy certain amenities derived from their proximity to valuable natural resources and recreational opportunities. But, that proximity puts those communities at elevated risk. Population centers along the nation's coastal waters have seen pronounced growth over the past fifty years. Fifty three percent of the total U.S. population lives in the 17% of land area that comprises the coastal zone. This trend is accelerating wetland loss and exacerbating pollution. Also, with the concentration of growth in coastal regions comes increased vulnerability to tropical storms, storm surge, coastal flooding, coastal erosion and sea level rise. Poor communities in these high-risk areas can be especially vulnerable. Certainly, the extent of the devastation of Hurricane Katrina was most pronounced because of the relatively more impoverished population, especially those without reliable transportation, who resided in some of the most flood-prone areas.

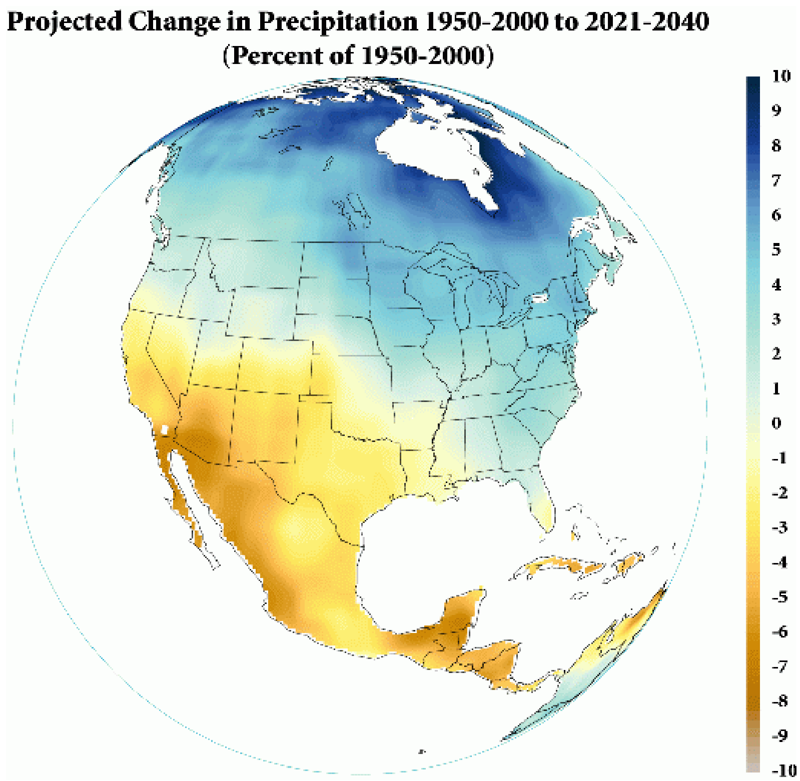
While we anticipate that many Americans will be only marginally affected by climate change in the next 50 years, we conclude that some portion of the population and some places where people live and work will be seriously and disproportionately impacted. The elderly, the very young, those with disabilities and some chronic conditions (e.g., cardiopulmonary illnesses), those who live alone and the poor will be at greater risk to climate change. Similarly some places, including urban heat islands, coastal zones, and arid regions, are relatively more at risk.

Box 4 Perpetual Drought in the Southwest: Water Supply at Risk

The trend toward a hotter and drier southwestern U.S. has begun and is expected to be evident within the next 15-20 years. Drought conditions are expected to resemble the Dust Bowl of the 1930's and the more localized drought of Texas in the 1950's. While those conditions were severe, they were not permanent. The current trend appears to be moving toward a permanent drought. The Columbia University study, led by Richard Seager, examined output from 19 climate models that simulated 49 projections of future temperature, rainfall, and evaporation in the Southwest. All but three of the projections concluded that the region would face serious increase in drought as early as 2021. The area within the U.S. affected by the drought is expected to include all of Texas and parts of New Mexico and Arizona (see Figure 2.4). Water resources will become more limited in a region that is already water scarce. Texas' 2007 State Water Plan proposes doubling the state's water supplies between 2010 and 2060. This plan calls for spending in access of $30 billion on new reservoirs, pipelines and other infrastructure.

Source: R. Seager, M.F. Ting, I.M. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, N. Naik, 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science*, DOI: 10.1126/science.1139601

Figure.4 Projected change in precipitation for the 2021-2040 period minus the average over 1950-2000 as a percent of the 1950-2000 precipitation. Results are averaged over simulations with 19 different climate models. Figure by G. Vecchi.



2.3. How can adaptation strategies reduce the impacts of climate change? [see Sections 3.5, 4.3]

Strategies for adapting to climate change hinge on building resilient communities across the United States. Resilient communities are those characterized both by their demonstrated capacity for sustainable development across time and by their ability to adopt strategies to successfully adapt to climate change and co-occurring changes in non-climate factors. Sustainable development is that which satisfies the needs of present generations without compromising the resources – natural and human-made – that will allow future generations to meet their needs. Sustainability inherently promotes strong inter-generational equity.

In this section, we examine the desirable characteristics of communities and identify those characteristics that increase resilience to climate change. Even if climate change itself may not be the most serious threat to sustainability, considering climate change impacts in a multi-change context can encourage and facilitate processes that lead to progress in dealing with other stressors. We consider how desirable features in communities have evolved to include urban planning concepts such as sustainability and smart growth. Finally, we consider a number of key adaptation strategies that may promote resilience to climate change in the United States.

2.3.1. Desirable communities and resilience to climate: A post-WWII perspective on development

After the turn of the 20th century, the rural population in the United States fell as farmers were displaced by mechanization and migrated in large numbers to urban factory jobs. The growth of urban centers, especially on the East and West coasts, mirrored the growth of the baby boom generation after World War II. Communities developed as more- or less-desirable based, at least in part, on their responsiveness to the needs of growing baby boom families.

Following World War II, metropolitan areas began to sprawl from city centers to the suburbs. The move to the suburbs was evidence of the gaining popularity of the automobile and government-insured home loans. The penetration of the passenger car into nearly every household led to reliance on the car for daily trips to work and school and errands. The introduction of the family car into American life was central in determining the development and the desirability of communities. Lengthy car commutes became common, if not the rule, in cities across the country.

But, there are tradeoffs related to automobile ownership. The costs to owners include the cost of the vehicle, taxes, insurance, maintenance, fuel, and parking and the costs associated with idling in congested traffic. The benefits realized by car owners include mobility, independence, convenience, and freedom. Beyond individual costs and benefits, there are social costs to car ownership that accrue to communities, including: demands for road repair and maintenance, air pollution from vehicle emissions, injury and death from car crashes, demands for public safety and law enforcement, and demands for urban planning to accommodate vehicle traffic while providing viable mass-transit options. Coupled with the unprecedented growth of the family car in the United States, federal and state transportation planning has revolved around construction of “super highways.” The interstate highway system has been a huge success. Suburban development has largely been supported because of transportation infrastructure that promises to bring jobs in urban centers within reach of a reasonable commute.

In all, the success of post World War II communities in the United States was derived from their having met the requirements of citizens for infrastructure (including sanitation, water supplies, electric and natural gas utilities, telephone service), for the provision of public safety and of health care and public health services, road construction, free or inexpensive recreational opportunities, public schools, arts and entertainment, and strong economic growth and available jobs.

2.3.2. Desirable communities and resilience to climate: A 21st Century concept.

With urban sprawl – the extension of urban areas into more and more remote suburban areas – accrues negative environmental, socioeconomic, and public health outcomes. The cost of the construction and maintenance of highway infrastructure and air pollution associated with billions of vehicle miles has caused reconsideration of the form and utility of communities.

Sustainable development is an alternative to traditional urban/suburban settlement patterns. The focus on sustainability has evolved in recent years in response to the impacts of individual consumption and to the collective footprint of communities on natural resources, ecosystem destruction, pollution, growing inequality in cities, the degradation of human living conditions and human-induced climate change. The emphasis of sustainable development is on creating livable communities and promoting physical well-being and desirable lifestyles. Put slightly differently, sustainability is realized as resilient communities. Resilience is measured by a community's capacity for absorbing climate changes and the shocks of extreme events without breakdowns in its economy, natural resource base, or social systems.

Smart growth has been described as the alternative to sprawl, traffic congestion, disconnected neighborhoods and central city decay. It explicitly considers long-term costs and consequences of growth and not just near-term benefits. For instance, a focus on mass transit can improve quality of life and encourage a healthier pedestrian-based lifestyle with less pollution. The community of the 21st Century is moving away from suburban sprawl, long commutes, vehicle emissions, and sedentary lifestyles and adopting sustainable development practices that will cushion the impacts of climate change on American communities and enhance their overall resilience.

2.3.3. The capacity for adaptation: strategies for responding to climate change.

There are substantial opportunities in the United States for individuals and communities to minimize the negative impacts of climate variability and change while maximizing the benefits. People have always adjusted or adapted to prevailing climate conditions. The adaptive capacity of the United States is considerable but that capacity has not been uniformly adequate to avoid significant losses and disruption in the aftermath of extreme weather events. Hurricanes, wild fires, river flooding, and other extreme events have tested readiness and response. Long-term changes in average and extreme conditions are expected to cause significant, widely distributed effects. To date, responses have tended to be decentralized and unorganized with uneven results.

The degree of adaptation that will be required by climate change depends on an array of factors, including:

- the current burden of climate-sensitive outcomes,
- the effectiveness of current interventions,
- projections of where, when, and how quickly the burdens to health and welfare could change with changes in climate and climate variability,
- 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.

Although there are uncertainties about future climate change, failure to invest in appropriate adaptation responses may leave communities poorly prepared and increase the probability of adverse consequences. Whether it entails relocating populations and activities away from vulnerable areas, adopting technologies that reduce the sensitivity of the built environment, institutional changes to improve capacities for preparedness and response to extreme events, or no-regrets policies that improve resilience to projected changes, the choice of adaptation will be as targeted and extensive as the climate impact it is designed to address. Climate change challenges the resolve and capacity of individuals and communities to plan and implement adaptive responses.

Important strategies for adaptation to climate impacts. Potential adaptation strategies for individuals and communities include:

1. <u>Changing the location of people or activities</u> – especially as such solutions address the costs of sustaining built environments in vulnerable areas. Strategies here address not only out-migrations from areas in the immediate aftermath of an extreme event but also more sustained or even permanent moves from vulnerable areas to safer or more desirable locations. Siting and land use policies can be used to encourage movement from more vulnerable areas to less, to add resilience to new construction within vulnerable areas, to increase awareness of climate-related hazards and risks, and to assist the disadvantaged (see Box 2.4).

2. <u>Changing the spatial form of communities</u> to improve sustainability of the built environment, to reduce lengths of daily trips to work and school with associated decreases in emissions, and to encourage green spaces and green buildings. A widely-used tool for achieving smart growth is the local zoning law. Through zoning, new development can be restricted to specific areas and density incentives can be offered for brownfield or greyfield land. Zoning can also be used to establish parking set asides as well as set-asides for parks and other community amenities.

3. <u>Technological change that reduces the sensitivity of people and their environments</u> to climate by adopting innovations that improve individual and community well being. Technological “fixes” may be used to reduce sensitivity of physical infrastructure, including updating sewer systems to decrease combined sewer overflows (CSOs), updating levee systems, and coastal hardening. For example, the U.S. Army Corp of Engineers (USACE) is developing technology-based responses for reservoir management to accommodate uncertain spring runoff and to allocate water storage among agricultural, domestic, and industrial needs. In addition, advances in technology can substantially increase our capacity for solving individual and collective health problems related to climate change. Adaptive strategies that are protective of human health involve a range of technologies, including watch-warning systems, air conditioning, pollution controls, vector control, vaccinations, and water treatment.

4. <u>Institutional change to improve coping capacity</u>, including assuring effective governance, providing financial mechanisms for increasing resiliency, improving coordination across multiple jurisdictions, targeting assistance programs for impacted segments of the population, and adopting sustainable community development practices. Policy instruments include zoning, building and design codes, terms for financing, and early warning systems. Institutional change to improve coping capacity can include coordination of governmental responses to weather-related emergencies, mandatory flood insurance for at-risk property

owners, discontinuation of underwriting for areas with a history of repeated insurance losses, incentives to subsidize permanent out-migration from at-risk areas, building codes and zoning ordinances that improve the durability of all new construction in at-risk areas.

5. “No regrets” strategies or low-net-cost policy initiatives that add resilience to communities and to physical capital – e.g., in coastal areas changing building codes for new construction to require coping with projected amounts of sea-level rise over the expected lifetimes of the structures. No regrets policies generate net social benefits whether or not there is climate change.

6. The choice of strategies from among the options is likely to depend on “co-benefits” in terms of other social, economic, and ecological driving forces, the availability of fiscal and human resources, and political aspects of “who wins” and “who loses.”

Aftermath of the 1997 Red River of the North flood and downtown Grand Forks, North Dakota, fire. Source: U S Geological Survey, 1997. http://nd.water.usgs.gov/photos/1997RedFlood/

Figure 2.4 Relocation in the Aftermath of the 1997 Red River Flood

The Red River Flood of 1997 occurred during April and May during the annual thaw of the River and its tributaries. The cities of Fargo, ND and Winnipeg were affected, as were the communities of Grand Forks and East Grand Forks where flood waters spread to as far as 3 miles inland. The flooding accompanied the rising river and overland flooding as the Red River was unable to adequately drain snowmelt. The Red River is a northward flowing river in which ice derived from its southern reaches meets freshly broken ice as it flows north, leading to slowing or damming of the water flow. Overall there was $2 billion in damages to Grand Forks and East Grand Forks. Thousands of people relocated after the flood. Grand Forks lost 3% of its population from 1997 to 2000, while East Grand Forks lost nearly 17% of its residents. There was no loss of life associated with the flood event. Winnipeg survived the Red River flood, because an emergency flood channel had been constructed around the city decades earlier.

Source: North Dakota State University. http://www.ndsu.edu/fargogeology/whyflood.htm; U.S. Geological Survey, North Dakota Water Science Center, 1997

2.4. Conclusion.

The first section of this chapter examined how climate change is likely to affect people and communities in the United States, how projected climate change will be experienced across the nation, and how non-climate factors might interact with climate factors to realize complex impacts. That section briefly summarized impacts on human health, human settlements, and human welfare.

The second section considered how climate change is likely to affect most Americans, concluding that, in the near term, many Americans are likely to be only marginally affected by climate change. Nonetheless, the report finds that some people and some places will be especially vulnerable to climate change. Those who live in arid, drought-prone places are at risk as are those located in coastal zones and those living in urban areas where extreme heat exacerbates negative health outcomes. Finally, populations are at risk whose age (very young and very old), poverty, and pre-existing conditions and disabilities put them at increased risk.

The third section explored how adaptation strategies can be developed to reduce the impacts of climate change in the United States and how an overall strategy of developing resilient communities may improve outcomes in both near and long-term time horizons. By investing in a range of adaptation strategies, including, for example, relocating population centers, adapting the spatial form of communities, employing new technologies, adapting institutions, and improving resilience, American communities can successfully respond to the challenges of climate change. In addition, resilient communities that succeed in focusing on long-term sustainable development, e.g., via smart growth models, will be best prepared for the challenges posed by climate variability and change. Central to the success of sustainable communities is the explicit inclusion of climate change risks in the development of communities and in the planning for and management of natural resources.

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Synthesis and Assessment Product 4.6

Chapter 3

Effects of Global Change on Human Health

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3.1 Introduction

Weather, climate variability, and climate change can affect health directly and indirectly. Directly, extreme weather (floods, droughts, windstorms, fires and heatwaves) 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. 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 variability and change on human health in the United States was published in 2000 as part of the First National Assessment of the Potential Impacts of Climate Variability and Change undertaken by the U.S. Global Change Research Program. This 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. 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 U.S. 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).

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 adaptive 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 variability and change. Part 1 focuses on climate-related impacts on human morbidity and mortality from extreme weather, vector-, water- and foodborne illnesses, including zoonotic 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 U.S. or in Canada, Europe, and Australia, where results may provide insights for U.S. populations.

This chapter first summarizes the current burden of climate-sensitive health determinants and outcomes for the U.S., before assessing the potential health impacts of global change. Two types of studies are assessed: those that increase our understanding of the associations between weather variables and health outcomes, and those that project the burden of health outcomes using climate scenarios. The first type of study raises potential concerns, assuming exposure-response relationships do not change.

It is important to note that the assessment focuses on how global 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.

Part 2 focuses on 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.

3.2 Climate-Sensitive Health Outcomes in the U.S.

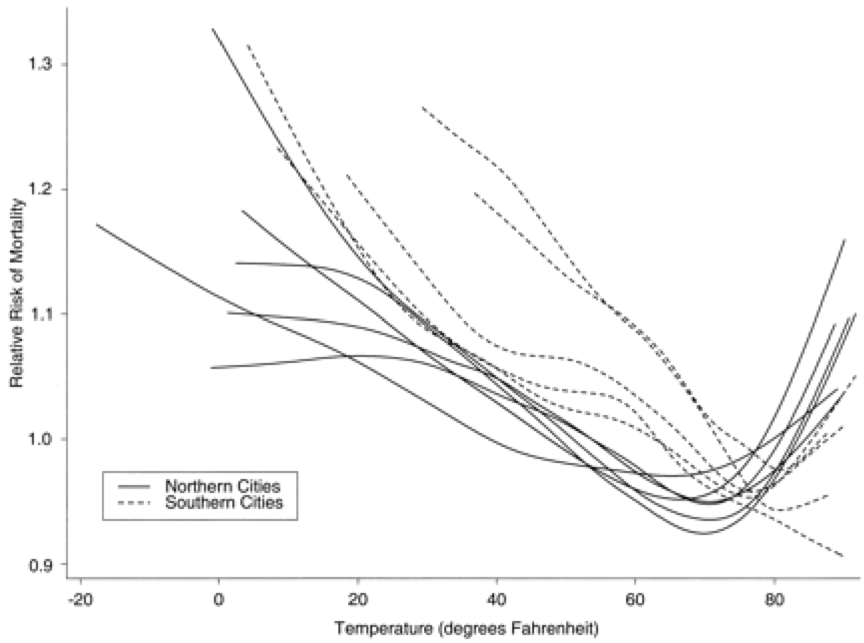
Extreme Weather

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 (see Figure 1; relative risks calculated using multiple regression analysis) (Braga et al. 2001). 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 under estimates of the total mortality associated with heatwaves. Heat is expected to contribute to the exacerbation of chronic health conditions, and several analyses have seen associations with cause-specific mortality-cardiovascular, renal, respiratory, 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 U.S. are those that occurred in 1980 (St. Louis and Kansas City, Missouri), 1995 (Chicago, Illinois), and 1999 (Cincinnati, Ohio; Philadelphia,, Pennsylvania; and Chicago). In all these episodes, the highest death rates 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). EPA is funding additional research on morbidity outcomes since the data are readily available from administrative datasets (EPA 2006a).

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 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. °C = 5/9 x (°F – 32). (Curriero et al. 2002) Permission to use: journals.permissions@oxfordjournals.org.



Urban heat islands may increase heat-related mortality 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).

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).

Cold

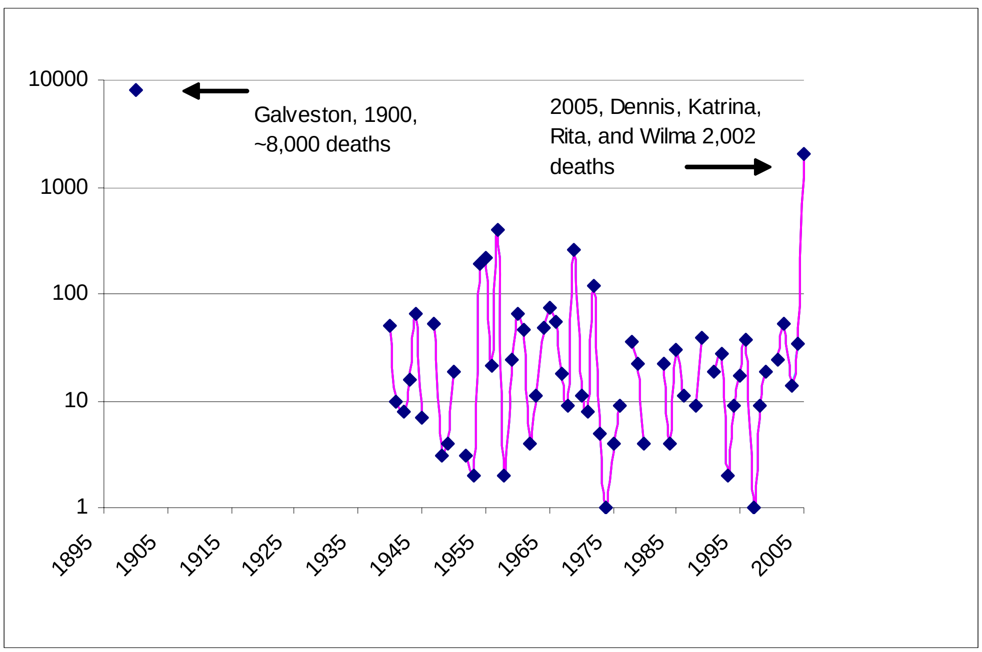
From 1979 to 2002, an average of 689 reported deaths per year (range 417-1,021), totaling 16,555 over the period, were attributed to exposure to excessive natural cold (Fallico et al. 2005). Cold also contributes to deaths caused by respiratory and cardiovascular diseases, so the overall mortality burden 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 a 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); and being female, having pre-existing respiratory illness (Wilkinson et al. 2004), lack of protective clothing (Donaldson et al. 2001), income inequality, fuel poverty, low residential thermal standards (Healy 2003), and living in nursing homes (Hajat et al. 2007).

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, 2006c) 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 shows the annual number of deaths attributable to hurricanes in the U.S. 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 in 2005 (NOAA, 2007). The 2005 hurricane season doubled the estimate of the average number of lives lost to hurricanes in the U.S. over the previous 65 years.

Figure 2. Annual Deaths Attributed to Hurricanes in the United States, 1900 and 1940-2005



Source: NOAA, 2007

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).

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 arbitrarily differentiate between zoonotic and water- and foodborne diseases, although many water- and foodborne disease are zoonotic.

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 U.S. 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). At the same time, other diseases expanded 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). 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 U.S. 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 U.S. and in other developed temperate countries since the First National Assessment,. Overall, these studies provide evidence that climate affects vector and tick abundance and distributions of vectors and ticks that can carry West Nile virus, Western Equine encephalitis, Eastern Equine encephalitis, Bluetongue virus, and Lyme disease, and perhaps disease risk, but in 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.

Waterborne and Foodborne Diseases

Water and foodborne diseases continue to cause significant morbidity in the U.S. 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). Likewise in drinking water outbreaks of known etiology, bacteria were the most commonly identified agent (29%; primarily *Campylobacter*), followed by parasites and viruses, which were 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 annually in the U.S., including over 900,000 hospitalizations and over 6,000 deaths. 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. Of the cases with known etiology patterns differ somewhat from that reported for outbreaks, with the highest frequency of illness 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). Clearly, 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 influence the pathogen directly by influencing its growth, survival, persistence, transmission or virulence. Likewise, 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). 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 or facilitate transmission of pathogens or affect the ecology and/or habitat of zoonotic reservoirs.

Studies in North America (U.S. 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 U.S., 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.*, 2005b). *Campylobacter* spp. 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 U.S. and is the most widespread zoonotic disease in the world (Meites *et al.*, 2004). 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.

Vibrio spp. (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* spp. 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, it has been suggested that 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* spp. has been noted in northern Atlantic waters of the U.S. coincident with warm water (Thompson *et al.*, 2004). Additionally, although most cases of *V. vulnificus* are attributed to Gulf Coast states, this species have been isolated from temperate and northern waters in the U.S. (Pfeffer *et al.*, 2003; Randa *et al.*, 2004).

The most striking example of 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. Evidence is highly suggestive that increasing global temperatures will lead to an increased burden of disease associated with certain *Vibrio* spp., 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 U.S. 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 per 100,000 of cryptosporidiosis were reported in the U.S. (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 U.S.; 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 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 may lead to increased exposure among certain groups, especially children.

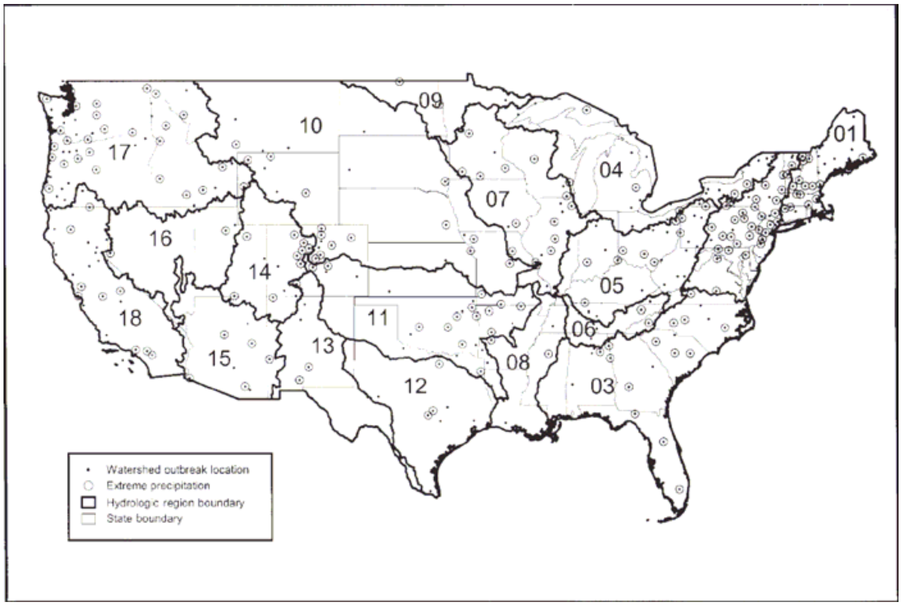
Naegleria fowleri is a free-living amboeboflagellate found in lakes and ponds at warm temperatures, either naturally or in thermally polluted bodies of water. While relatively rare, infections are almost always fatal (Lee *et al.*, 2002). *N. fowleri* can be detected in environmental waters at rates up to 50% (Wellings *et al.*, 1977) at water temperatures above 25^{o} C (Cabanes *et al.*, 2001). Cases are consistently reported in the U.S.; 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 U.S. than elsewhere in the world (Marciano-Cabral *et al.*, 2003). Given its association with warm water, elevated temperatures might be expected to 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 hepatis 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 3). Similarly, Thomas *et al.* (2006) found that 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 3. Drinking Waterborne Disease Outbreaks and 90%-ile Precipitation Events (a two month lag precedes outbreaks); 1948 – 1994.



Source: Curriero *et al.*, 2001

Flood waters may increase the likelihood of contaminated drinking water and lead to incidental exposure to standing flood waters. 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).

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 U.S. 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 U.S. 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 Nino 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.

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 may affect its incidence and geographic range.

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) 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. It has been firmly established that breathing ozone results in short-term, reversible decreases in lung function as well as burning of the cells lining the lungs. 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, especially with physical exertion, outdoors during episode periods 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.[1] 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, 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 diabetes, children and older adults. Because the mortality risks of PM2.5 appear to be mediated through narrowing of arteries and resultant heart impacts, persons or populations with high blood pressure and/or pre-existing heart conditions are likely to be at increased risk. In a study of mortality in relation to long-term PM2.5 concentrations in 50 U.S. cities, persons without a high school education demonstrated higher concentration/response functions that those with more education (Pope *et al.*, 2002), which may reflect differential exposures or differential responses given exposure, or some combination of both.

3.3 Projected Health Impacts of Global Change in the US

Heat-Related Mortality

Determinants of how climate change could alter heat-related mortality include actual changes in the mean and variance of future temperature; factors affecting temperature variability at the local scale; demographic 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. Residential and industrial development will increase over the coming decades, which will likely 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.

[1] 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.

Table 1 summarizes projections of temperature-related mortality either in the U.S. or in temperate countries whose experience is relevant to the U.S. (Dessai 2003) (Woodruff et al. 2005) (Knowlton et al. in press) (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.

Table 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 2020's, 97-255% in 2050s, depending on adaption
8 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).

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 U.S.), improved health care, and other factors. To use these results to suggest that increases in heat-related mortality may not occur in the U.S. (Davis et al. 2004), it is necessary to assume that mortality during temperature extremes will continue to decline at the same rate, even though the percentage of the population with access to air conditioning is high in most regions and improvements in health care have stalled in recent years. Further, population level declines may obscure persistent mortality impacts in vulnerable groups.

Hurricanes, Floods, and Wildfires

No studies have projected the future health burdens of extreme weather events. However, there is a theoretical basis for concern that climate change will 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 limitations of 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.

Although, on average, the number of extreme precipitation events has increased over time, (Balling Jr. and Cerveny, 2003; Groisman *et al.*, 2004; Kunkel, 2003), seasonal and regional patterns are not as consistent (Groisman *et al.*, 2004). Overall, general circulation models (GCMs) project increases in mean precipitation with a disproportionate increase in the frequency of extreme precipitation events (Senior *et al.*, 2002). The IPCC concluded that it is very likely (>90% certainty) that trends in extreme precipitation will continue in the 21st century (IPCC, 2007). Kim (2003) used a regional climate model to project that a doubling in CO2 concentrations in roughly 70 years could increase by roughly 33% the number of days with at least 0.5 mm of precipitation across the study's defined elevation gradients in the western U.S.

GCMs project that key meteorological variables for wildfires, as well as vegetative cover, will be affected by climate change. Climate change may also affect human activity, notably patterns of residential development and resource use, resulting in direct and indirect pressures on wildfires. Therefore, there is reason to believe climate change could affect the incidence and severity of wildfires in the U.S.

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. All else equal, these increases mean more U.S. residents will be at risk for future extreme weather events and that more health impacts can be anticipated.

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 U.S. Studies suggest that temperature influences the distributions of Ixodes spp. ticks that transmit pathogens causing Lyme disease in the U.S. (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, based on a multivariate statistical analysis of current areas of risk, to decrease the geographic range of TBE in areas of lower latitude and elevation as transmission expands northward (Randolph and Rogers, 2000).

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). 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.

Table 2. Possible Influence of Climate Change on Climate Susceptible Pathogens and/or Disease

Pathogen	Exposure Routes	Possible Influence of Climate Change	Confidence in Changes[a]	References
Bacteria				
Salmonella	**Food**	**Increasing temperature associated with increasing clinical cases**	**High**	**D'Souza *et al.*, 2004; Kovats *et al.*, 2004a; Fleury *et al.*, 2006; Naumova *et al.*, 2006**
		Precipitation and run-off associated with increased likelihood of contamination of produce	**Medium[b]**	**Haley 2006; Holley *et al.*, 2006**
	Water	**Increasing temperature associated with increasing clinical cases**	**High**	**D'Souza *et al.*, 2004; Fleury *et al.*, 2006; Kovats *et al.*, 2004a; Naumova *et al.*, 2006**
		Shifts in habitat and range of reservoirs may influence potential contact	**Medium[b]**	
Campylobacter	**Food**	**Increasing temperatures may contribute to**	**Medium**	**Newel, 2002**

		seasonal carriage rates among reservoirs and thereby increase rates		
	Water	**Increased precipitation may increase likelihood of contamination of drinking water sources due to run off**	**Medium**	**Auld *et al.*, 2004; Vereen *et al.*, 007**
		Increasing temperatures may contribute to seasonal carriage rates among reservoirs and thereby increase rates	**Medium**	**Newel, 2002**
		Shifts in habitat and range of reservoirs may influence potential contact	**Medium[b]**	
***Vibrio* spp.**	**Food**	**Increased ambient temperatures associated with growth in post-harvest shellfish and increased disease**	**Very High[c]**	**Cook, 1994**
	Water	**Increasing temperature associated with higher environmental prevalence and disease**	**High**	**Janda *et al.*, 1988; Lipp *et al.*, 2002; McLaughlin et al. 2005; Dziuban *et al.*, 2006**
		Increasing temperature associated with range expansion	**High**	**McLaughlin *et al.*, 2005**
		Increased precipitation and fresh water run off leads to depressed estuarine salinities and increase in some *Vibrio* spp.	**Medium**	**Lipp *et al.*, 2001b; Louis *et al.*, 2003**

		Sea level rise and or storm surge increase range and human exposure	**Medium**	**Lobitz *et al.*, 2000**
***Leptospira* spp.**	**Water**	**Increased temperatures may increase range**	**Medium**	**Bharti *et al.*, 2003; Howell and Cole, 2006**
		Increased precipitation and run off precedes outbreaks	**High**	**Meites *et al.*, 2004**
Viruses				
Enteroviruses	**Water**	**Potential increase in temperature associated with increased peak clinical season (summer)**	**Low[d]**	
		Increase in temperature associated with increased decay and inactivation of viruses in the environment	**Medium**	**Gantzer *et al.*, 1998; Wetz *et al.*, 2004**
		Increased precipitation associated with increased loading of viruses to water and increased disease	**High**	**Lipp *et al.*, 2001a; Frost *et al.*, 2002; Fong *et al.*, 2005**
Norovirus	**Food**	**Increased temperature leads to decreased retention of virus in shellfish**	**Low[e]**	**Burkhardt and Calci, 2000**
		Increased precipitation associated with increased loading of viruses to crops and fresh produce	**Medium[b]**	**Miossec *et al.*, 2000**
	Water	**Increase in temperature associated with increased decay and inactivation of**	**Medium**	**Griffin *et al.*, 2003**

		viruses in the environment		
		Increased precipitation associated with increased loading of viruses to water and increased disease	**High**	**Goodman *et al.*, 1982**
		Increase in temperature associated with shorter peak clinical season (winter)	**Low[e]**	
Rotavirus	**Water**	**Increase in temperature associated with increased decay and inactivation of viruses in the environment**	**Medium**	**Rzezutka and Cook, 2004**
Parasites				
Naegleria fowleri	**Water**	**Increased temperature associated with expanded range and conversion to flagellated form (infective)**	**Medium[b]**	**Cabanes *et al.*, 2001**
Cryptosporidium	**Water**	**Increased precipitation associated with increased loading of parasite to water and increased disease**	**High[f]**	**Curriero *et al.*, 2001; Davies *et al.*, 2004**
Giardia	**Water**	**Increased temperature associated with shifting range in reservoir species (carriers) and expanded disease range**	**Medium[b]**	**Parkinson and Butler, 2005**
		Increased precipitation associated with increased loading of parasite to water and increased disease	**High[f]**	**Kistemann *et al.*, 2002**

[a] Based on both research reports and likelihood of the event This confidence scale is based on conditional probabilities such that low represents an occurrence of <5/10, medium 5-6/10, high 8/10 and very high >9/10.
[b] Likelihood of event is probable but little research has addressed the issue
[c] Evidence is highly supportive but adaptive measures (refrigeration) would reduce this effect
[d] Geographical evidence supports this (infections show little seasonality near the equator) but no data are available
[e] There is no evidence for direct control of temperature on seasonality of infection
[f] Evidence is highly supportive but adaptive measures (water treatment and infrastructure) would reduce this effect

Air Quality

The sources and conditions that give rise to elevated ozone and PM2.5 in outdoor air in the U.S. 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.

The influence of meteorology on air quality is substantial and well-established (EPRI, 2005), suggesting 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 pollutants in the atmosphere. The most severe U.S. air pollution episodes occur with atmospheric conditions that limit both vertical and horizontal dispersion over multi-day periods. Climate change will alter the temporal and spatial distributions of meteorologic factors, which could influence air quality. 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 concentrations. Though of great concern from a human health perspective, little research to-date has addressed climate impacts on anthropogenic particulate matter concentrations.

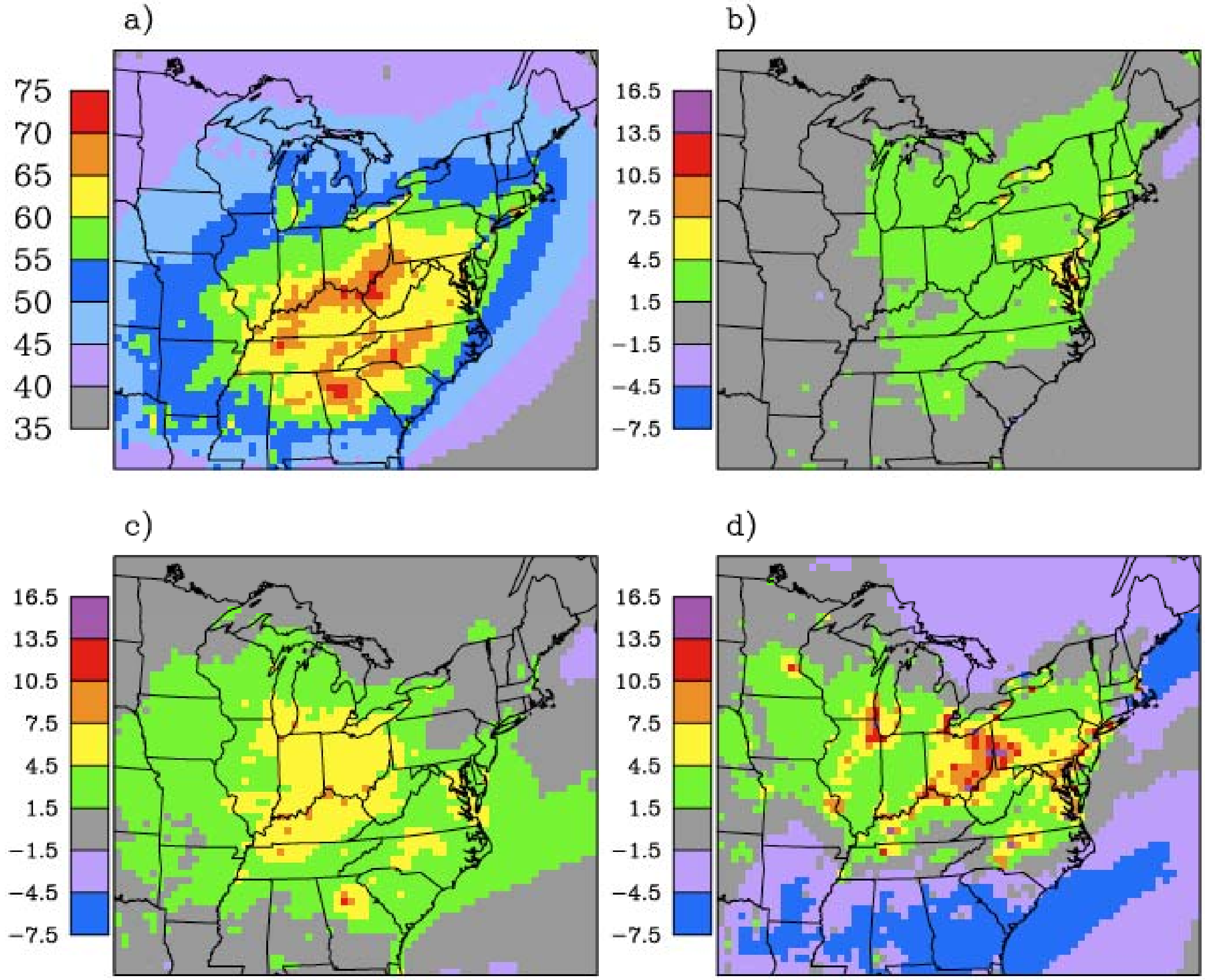
Leung and Gustafson (2005) used regional climate simulations for temperature, solar radiation, precipitation, and stagnation/ventilation, and projected worse air quality in Texas and better air quality in the Midwest in 2045-2055 compared with 1995-2005. Aw and Kleeman (2003) simulated an episode of 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 U.S., 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.

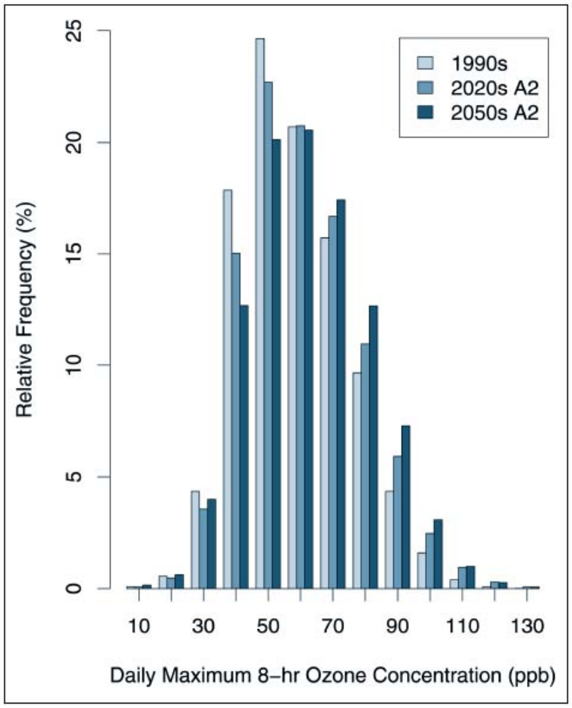
As part of the New York Climate and Health Study, Hogrefe and colleagues conducted local-scale analyses of air pollution impacts of future climate changes using integrated modeling (Hogrefe *et al.*, 2004a,b,c; 2005a,b) to examine the impacts of climate and land use changes on heat- and ozone-related 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 meteorologic 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 U.S. 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 U.S. 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 U.S. 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 4) (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 5).

Figure 4: (a) Summertime Average Daily Maximum 8-hour Ozone Concentrations (ppb) for the 1990s and Changes for the (b) 2020s, (c) 2050s, and (d) 2080s Based on the A2 Scenario Relative to the 1990s. Five consecutive summer seasons were simulated in each decade.



Source: Hogrefe et al., 2004a.

Figure 5. Frequency Distributions of Summertime Daily Maximum 8-hr Ozone Concentrations over the Eastern U.S. in the 1990s, 2020s, and 2050s based on the A2 Scenario.



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

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. However, 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. 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 U.S. (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%. 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:

- Both ozone and fine particle concentrations are likely to be affected by climate change.

- A substantial body of new evidence on ozone supports the interpretation that ozone concentrations will tend to increase in the U.S. as a result of climate change, all else being equal.

- Too few data yet exist for PM to draw firm conclusions about the direction or magnitude of climate impacts.

Vulnerable Subpopulations

"Vulnerability" is defined as the summation of all risk and protective factors that ultimately determine whether a subpopulation experiences adverse health outcomes, and "sensitivity" is defined as an individual's or subpopulation's increased responsiveness, primarily for biological reasons, to a given exposure. Specific subpopulations may experience heightened vulnerability for climate-related health effects for a wide variety of reasons. Biological sensitivity may be related to the presence of pre-existing chronic medical conditions (such as the sensitivity of people with chronic heart conditions to heat-related illness), developmental stage, acquired factors (such as immunity), and genetic factors (such as metabolic enzyme subtypes that play a role in vulnerability to air pollution effects). Socioeconomic factors also play a critical role in altering vulnerability and sensitivity to environmentally-mediated factors. They may increase 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 recognize populations that may experience synergistic effects of multiple risk factors for health problems, both related to climate change and related to other temporal trends.

Certain regions of the United States may experience increased risks for specific climate-sensitive health outcomes due to their baseline climate, abundance of natural resources such as fertile soil and fresh water supplies, elevation, or vulnerability to coastal surges or riverine flooding. Some regions may in fact experience multiple climate-sensitive health problems simultaneously.

An initial approach to identifying subpopulations with heightened vulnerability to climate-sensitive health outcomes is to consider the biological and socioeconomic risk factors for each health outcome (Table 3).

Table 3. Climate-Sensitive Health Outcomes and Particularly Vulnerable Groups

Climate Sensitive Health Outcome	**Particularly Vulnerable Groups**
Heat Stress	Elderly, chronic medical conditions, infants and children, pregnant women, urban and rural poor, outdoor workers
Air Pollution	Children, pre-existing heart or lung disease, diabetes, athletes and outdoor workers
Extreme Weather Events	Poor, pregnant women, those with chronic medical conditions, and 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 Illness	
A. Lyme Disease	Outdoor workers
B. Hantavirus	Rural poor, occupational groups
C. Dengue	Infants, elderly
D. Malaria	Immunocompromised, pregnancy genetic (G6PD status)

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 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 PSTD, depression, and dissatisfaction with ongoing life (Bokszanin, 2000; cited in Hajat *et al.*, 2003).

Pregnant women

Pregnant women are likely to be vulnerable to adverse health effects in the aftermath of extreme weather events, problems, including exposure to environmental toxins, limited access to safe food and water, psychological stress, and disrupted health care access. One review suggested increased incidence of adverse reproductive outcomes after Hurricane Katrina (Callaghan *et al.*, 2007). Pregnancy also confers increased susceptibility to a variety of climate-sensitive infectious diseases, including malaria and foodborne infections (Jamieson *et al.*, 2006).

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, 2004). Effects of ambient particulate matter on daily mortality tend to be greatest in older age groups (Schwartz, 1995).

Impoverished Populations

Even in the U.S., the greatest health burdens will 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.

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).

Box 1: 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 populations, such as hospital and nursing-home patients, older adults who required care within their homes, and individuals with disabilities (U.S. CHSGA, 2006). 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, 2006b). A quarter of the deaths indirectly related to the hurricane in Alabama were associated with preexisting cardiovascular disease (CDC, 2006d), 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).

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).

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 heat waves and other extreme weather events (EPA, 2006). As noted above, people with chronic medical conditions are also at risk of worsened status as the result of stressors and limited access to medical care during extreme events.

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 Lyme Disease (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.

Table 4 summarizes the climate-related vulnerability of specific U.S. subpopulations, based on age, underlying medical conditions, and socioeconomic status. Recognition of combined effects will aid efforts at public health intervention and disease prevention.

Table 4. Summary of Vulnerability to Climate-Sensitive Health Outcomes by Subpopulation

Groups with Increased Vulnerability	Climate-Related Vulnerabilities
Infants and Children	Heat stress, ozone air pollution, waterborne and foodborne illnesses, dengue, malaria
Pregnant women	Heat stress, extreme weather events, water and foodborne illnesses, malaria
Elderly / chronic medical conditions	Heat stress, air pollution, extreme weather events, water and foodborne illnesses, dengue
Impoverished / low socioeconomic status	Heat stress, extreme weather events, air pollution, vector-borne infectious diseases
Outdoor workers	Heat stress, ozone air pollution, Lyme disease, other vector-borne infectious diseases.

3.4 Priority Research Needs and Data Gaps

Few research needs 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 great appreciation of the complex pathways by which weather and climate affect health, and the understanding that many non-climatic, 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 pollution. Despite these advances, the body of literature remains small, limiting quantitative projections of future impacts. Considerably more research is needed to ensure the U.S. is adequately prepared to cope with projected changes in climate.

Research needs can be classified into:

- Increase understanding of exposure-response relationships, including identifying likely thresholds and particularly vulnerable groups, taking into consideration relevant factors that affect the geographic range and incidence of climate-sensitive health outcomes, including disease ecology and transmission dynamics. Research on morbidity relationships is particularly needed. Long-term data collection is needed, focusing on regions and populations likely to be particularly vulnerable. Also need are:

- Empirical studies to quantify the independent and joint effects of air pollution and weather on morbidity and mortality, with explicit evaluation of effect modification.
- Studies to quantify and better understand the adaptive response to heat stress.
- Evidence for early effects of changing weather patterns on climate-sensitive health outcomes.
- Surveillance systems targeted towards emerging infectious diseases, particularly those related to insect and animal vectors.
- Quantitative models of the possible health impacts of climate change that can be used to explore a range of socioeconomic and climate scenarios.
- Studies that model the two-way interactions of climate and air quality at global and regional scales.
- Studies that incorporate a full suite or "ensemble" of climate models and scenarios to examine potential future impacts.
- Increase understanding of the process of adaptation, including the costs of those interventions. For example, heatwave and health early warning systems are not inspiring appropriate behavior; further research is needed to understand how messages can be made more effective.
- Evaluation of adaptation measures. For example, evaluation of heatwave and health early warning systems, especially as they become implemented on a wider scale (NOAA, 2005), is needed to understand how to motivate appropriate behavior.
- Adaptation models to better understand the benefits and limits of specific policies and measures; and
- Comprehensive estimates of the co-benefits of mitigation policies. Methods to incorporate both direct health benefits as well as GHG mitigation benefits into local land use decisions.

In addition, policymakers need local and regional scale vulnerability and adaptation assessments to understand the potential risks and the time horizon over which those risks might arise; these assessments should include stakeholders to ensure their needs are identified and incorporated into subsequent research and adaptation activities.

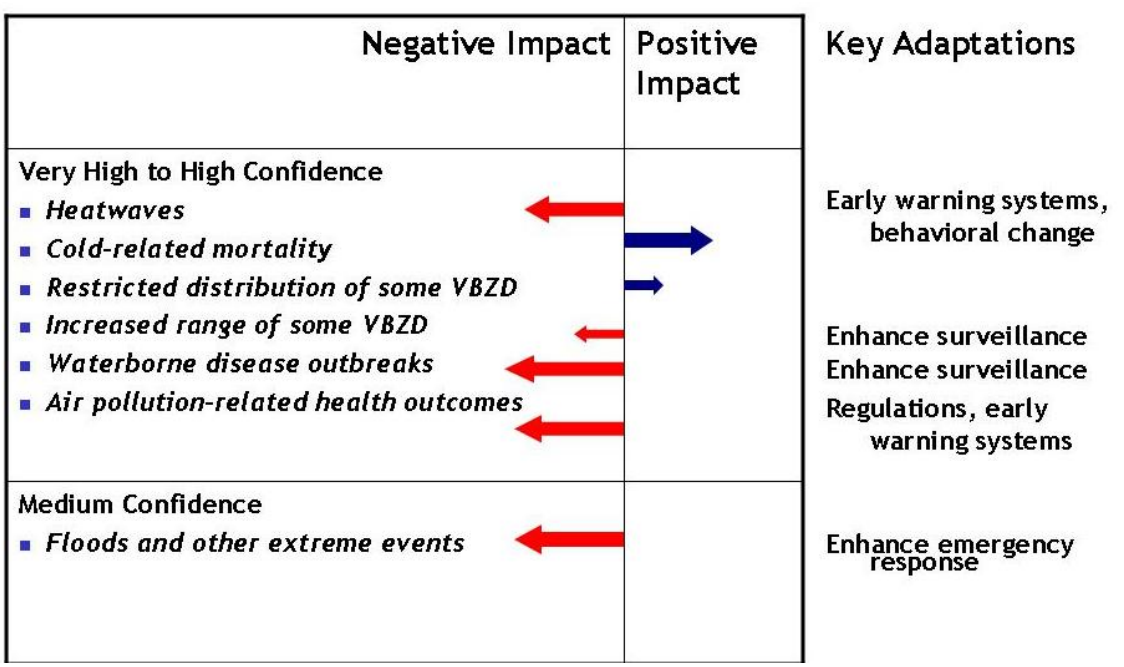
For extreme weather events, heatwaves, and food- and waterborne diseases, investments in infrastructure may be needed in some regions to provide protection against extreme events, to alter urban design to decrease heat islands, and to maintain drinking and wastewater treatment standards and source water and watershed protection.

Underlying these needs are requirements for long-term data collection on issues of potential concern, such as surveillance of the geographic range of vectorborne and zoonotic diseases, and better surveillance and reporting of food- and waterborne diseases. Downscaled climate projections to local and regional levels are needed. The growing concern over impacts from extreme events means that climate models are needed 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.

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 adaptation actions are needed now. 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. However, the nature of the risks posed by climate change mean that all adverse health outcomes will not be avoided. Figure 6 provides a qualitative summary of the relative direction, magnitude, and certainty of health impacts.

Figure 6: Summary of Relative Direction, Magnitude, and Certainty of Health Impacts



3.5 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. Further, as detailed in Part 1 of this chapter, climate change is likely to challenge the ability of current programs and activities to control climate-sensitive health determinants and outcomes. Preventing additional morbidity and mortality requires developing and deploying adaptation policies and measures that include specific consideration of the full range of health risks that are likely to arise with climate change.

In public health, prevention is the term analogous to adaptation. 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). Although there are uncertainties about future climate change, failure to invest in adaptation may leave communities poorly prepared and increase the probability of severe adverse consequences (Haines *et al.*, 2006a,b).

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 actions. A public 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 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.

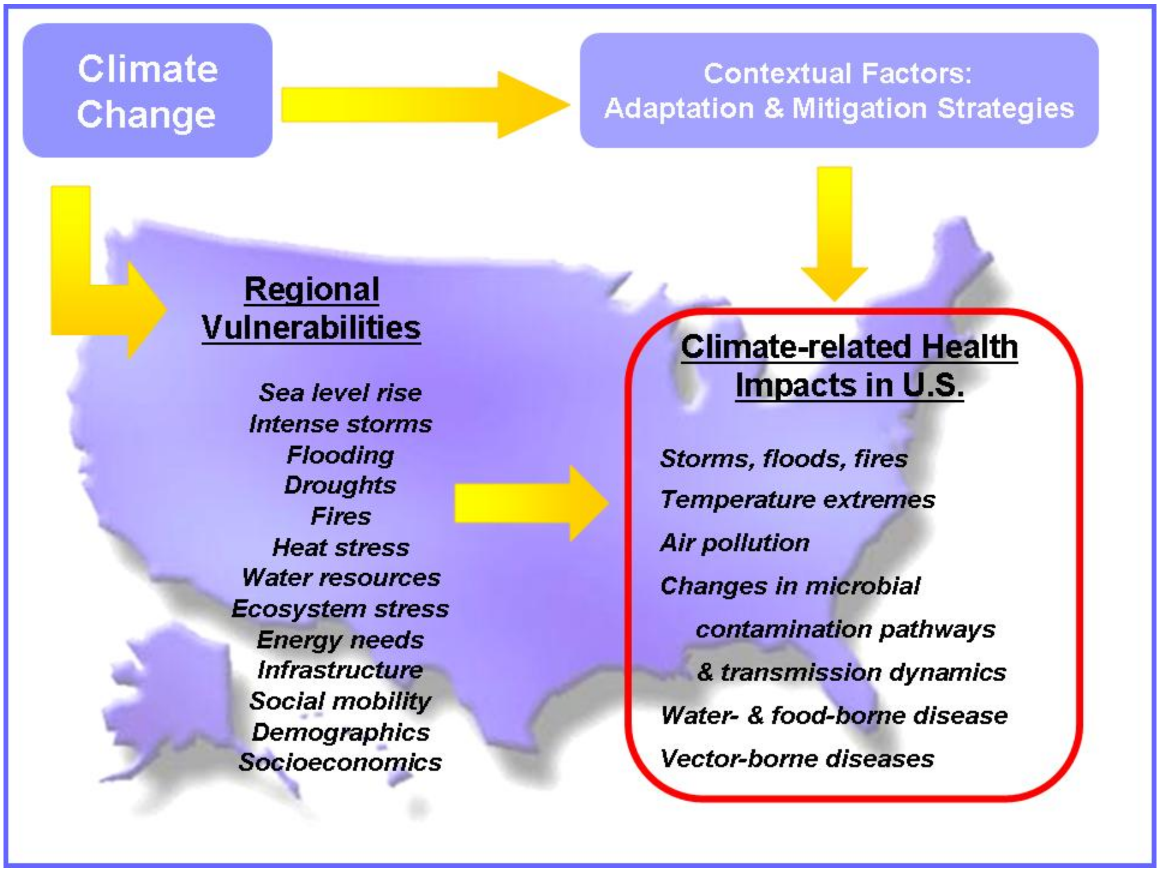
Adaptation policies and measures should address both projected risks and the regions and populations that currently are not well adapted to climate-related health risks. Because the degree and rate of climate change is projected to increase over time, adaptation will be a continual process attempting to prevent adverse impacts from changing exposures and vulnerabilities. History suggests that this process will likely be a step-function, with occasional large impacts (although these events can not be attributed to climate change, illustrative examples include Hurricane Katrina or the appearance and spread of West Nile virus) followed by changes in public health and other programs and practices to reduce future vulnerability. Obviously, 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.

This section focuses on adaptation to the potential health impacts of environmental change in the United States, and considers actors and their roles and responsibilities for adaptation, and adaptation measures to reduce projected climate change-related health risks.

Framework for Adaptation

Figure 7 provides a framework for adaptation. Adaptation activities take place within the context of slowly-changing factors that are partial determinants of the extent of impacts experienced and 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. Other factors that set the context within which adaptation measures are designed and implemented 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.

Figure 7: Framework for Adaptation



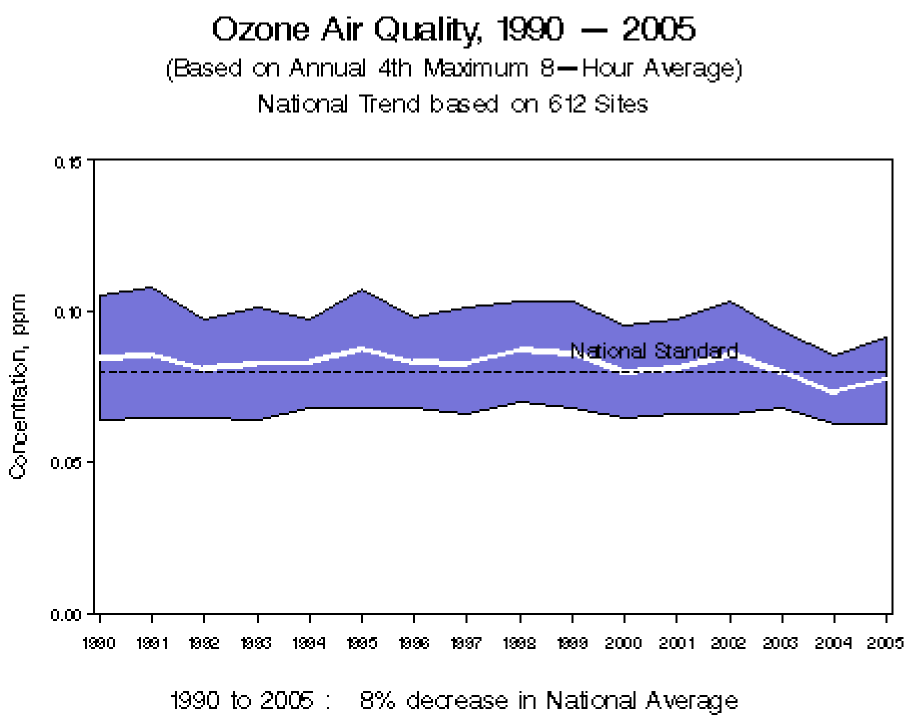
Actors and Their Roles and Responsibilities for Adaptation

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 (see example in Box 2). 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 ambulatory services and through emergency preparedness plans (Box 3). Early warning systems for extreme events 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 tools (Box 4). 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.

Box 2: Ensuring Safe Air and Drinking Water

The U.S. EPA is tasked with establishing and enforcing regulations to ensure the nation has safe air and drinking water. The Clean Air Act of 1990 requires EPA to set National Ambient Air Quality Standards for pollutants considered to be harmful to public health and the environment. There are two types of standards: primary standards that protect public health, including the health of sensitive populations, such as asthmatics and elderly citizens. Secondary standards set limits to protect public welfare. The six criteria air pollutants include ozone, nitrogen dioxide, and sulfur oxides. The ozone standard is currently under review. As shown in Figure 8, national concentrations of ozone decreased 8% decreased from 1990 to 2005 (www.epa.gov/airtrends/ozone.html), with large variability in local trends. Because climate change may increase ozone concentrations in some regions, more aggressive emissions controls may be needed to reduce ozone concentrations.

Figure 8: Ozone Air Quality, 1990-2005



Source: http://www.epa.gov/airtrends/ozone.html, accessed 12 February 2007

Box 3: 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), 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 4: Enhancing Surveillance for Mosquito-borne Diseases

Brownstein *et al.* (2004) is an example of recent research using GIS and other tools to facilitate surveillance and control of infectious diseases. In 2006, 1,419 West Nile virus (WNV) human cases, with 161 fatalities, were reported to the CDC from 45 states (http://www.cdc.gov/ncidod/dvbid/westnile/surv&controlCaseCount06_detailed.htm, accessed 12 February 2007). Although a national human surveillance system has been established, passive surveillance data are problematic because most cases of disease are relatively mild (so are unreported) and because of variability in disease reporting across counties and states. To improve targeting of prevention resources, Brownstein *et al.* (2004) developed a statistical method to estimate human disease risk early in the transmission season. Crude county-specific incidence rates were calculated in August 2003 based on weekly case numbers, and then random noise was removed. A conditional autoregressive model was then used to project counties that would experience a high incidence of WNV during 2003. Brownstein *et al.* (2004) also used their model to quantify the utility of nonhuman (e.g. bird and mosquito) surveillance. Quantitative mosquito data predicted 15-times more of the variation in human cases than quantitative bird data, emphasizing that active mosquito surveillance is the most sensitive marker of human risk. Unfortunately, not all states have effective active mosquito surveillance. This tool has the potential to identify high-risk counties before the major influx of cases during the transmission season, which would help target more effective disease prevention efforts.

Additional research and development are needed to ensure that surveillance systems account for and anticipate the potential effects of climate change. Surveillance systems will be needed in locations where changes in weather and climate may foster the spread of climate-sensitive pathogens and vectors into new regions (NAS, 2001). Understanding associations between disease patterns an environmental variables can 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).

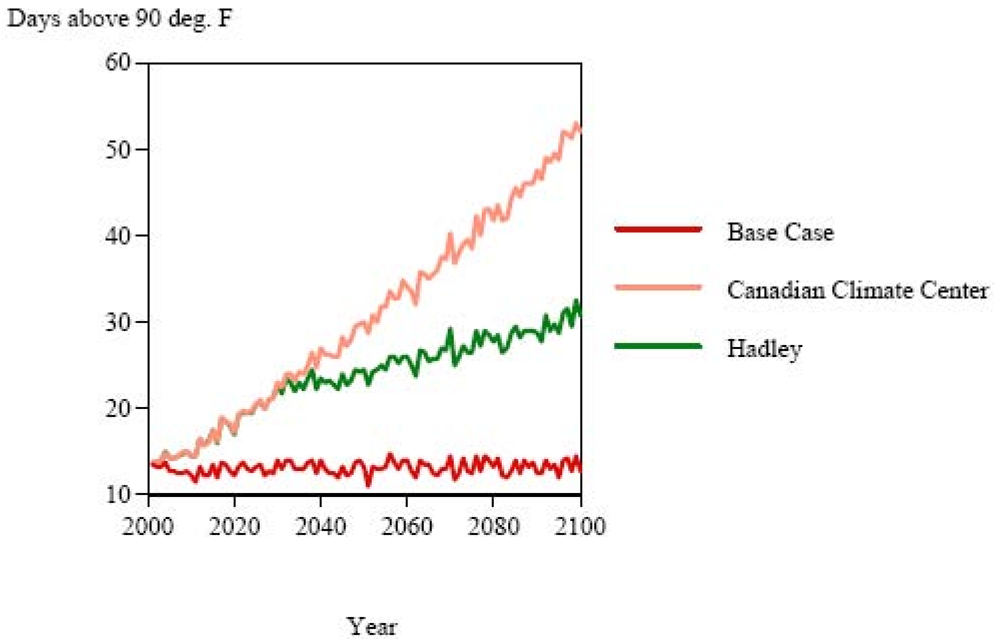
Surveys have not been conducted in the U.S. of the risk various actors responsible for coping with climate change-related health impacts. However, the growing numbers of city and state actions on climate change show increasing awareness of the potential risks. As of 1 February 2007, 393 cities representing 57 million Americans 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 CO2 and reduce urban heat islands. The New England Governors and Eastern Canadian Premiers developed a Climate Change Action Plan because of concerns about 'degradation in air quality and an increase in urban smog (with its associated human health impacts); public health risks; insect reproduction and the population of disease-bearing pests such as mosquitoes; the magnitude and frequency of extreme climatic phenomena' and availability of water (NEC/ECP, 2001). Action Item 7 focuses on the reduction and/or adaptation of negative social, economic, and environmental impacts. Activities being undertaken include a long-term phenology study, studies on temperature increases and related potential impacts, and the creation of a consortium of researchers and scientists.

Strategies, policies, and measures implemented by community and state governments, federal agencies, NGOs, and other actors can change the context for adaptation by sponsoring research and development to assess vulnerability (see Box 5) and to identify technological options available for adaptation, implementing programs and activities to reduce population vulnerability, and allocating 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. Adaptations should be designed to address projected health burdens.

Box 5: Projected Heat-Related Mortality in Metropolitan Boston (CLIMB, 2004)

An assessment was undertaken of metropolitan Boston's vulnerability to climate change-related temperature mortality. Analysis of temperature-mortality relationships for 1970-1998 identified 90ºF as the threshold above which mortality increased. A base climate case was created by using historical weather data to project regional temperatures to 2050, and then using a moving block bootstrapping method to project temperatures to 2100. Trends from two climate models (Canadian Climate Center and Hadley Centre) were superimposed on these projections to create time series data of future weather conditions that were consistent with past patterns and climate change trends. Figure 9 shows projected annual average number of days above 90ºF under the three scenarios.

Figure 9: Annual Average Number of Day above 90°F, Metropolitan Boston

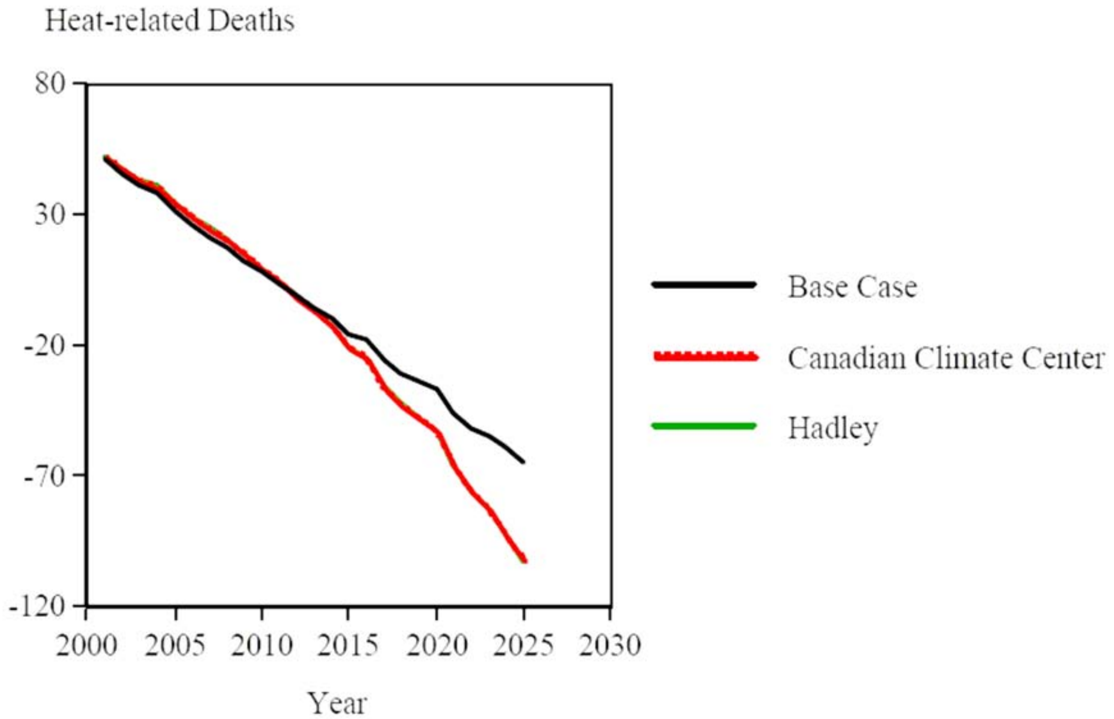


Source: CLIMB, 2004

A key adaptation assumption was that the observed approximate 50% decrease in heat-related mortality between 1970 and 1992 would continue. Figure 10 shows the projected annual heat-related deaths for metropolitan Boston under the three scenarios; a slight increase in mortality was projected until about 2010 under climate change, then a continual decline in mortality under all scenarios to 2100. The decline is more pronounced under the climate scenarios in which the frequency of extreme heatwaves increases, which was primarily due to assuming a continuation of historic trends in mortality declines.

This assessment highlights that even under assumptions of significant increases in adaptation, there may be short-term climate change-related increases in mortality. Taken at face value, these results suggest that metropolitan Boston is likely to be well adapted to future heat-related mortality. However, the observed decline in mortality includes increased use of air conditioning over the past 30 years, improvements in health care, and other changes. Continuing to achieve large reductions in heat-related mortality will require more aggressive efforts, such as implementing a heat early warning system and taking actions to reduce the urban heat island. Another factor to consider is that an aging population may be more susceptible to high temperatures. Overall, this assessment suggests the need for more adaptation.

Figure 10: Annual Heat-Related Mortality to 2030, Metropolitan Boston



Source: CLIMB, 2004

Table 5 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 vs 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. Vaccines are available for Lyme disease and are under development for others, such as West Nile virus.

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.

Table 5: Actors and Their Roles and Responsibilities for Adaptation

Actor	Reduce Exposures	Prevent Disease Onset	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	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 Monitor the air, water, and soil for hazardous exposures 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 decisions support tools for development of early warning systems Institute and maintain 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	Sponsor research and development on vaccines and other preventive measures Sponsor research and development on rapid diagnostic tools Provide low-cost vaccinations to those likely to be exposed	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
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	Develop and enforce watershed protection and safe water and food handling regulations (e.g., Clean Water Act)	Sponsor research and development on rapid diagnostic tools for food- and waterborne diseases	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 Pollution			
Individuals	Follow advice on appropriate	For individuals with certain respiratory	Seek treatment when needed

	behavior on high ozone days	diseases, follow medical advice during periods of high air pollution	
Community, State, and National Agencies	Develop and enforce regulations of air pollutants (e.g., Clean Air Act)	Develop scientific and technical guidance and decisions support tools for development and implementation of early warning systems Conduct education and outreach on the risks of exposure to air pollutants	Sponsor research and development on treatment options

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 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 6 lists some adaptation measures for heatwave, extreme weather events, vectorborne diseases, waterborne diseases, and air pollution. 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 in a particular region.

Table 6: Adaptation Measures to Reduce Climate Change-Related Health Risks

	Heatwaves	**Extreme Weather Events**	**Vectorborne Diseases**	**Waterborne Diseases**	**Air Pollution**
Legislative Policies	Alter building design and infrastructure codes to reduce urban heat islands	Improve land use planning	Develop and maintain effective vector surveillance and control programs that incorporate climate change concerns	Ensure watershed protection and water quality laws are resilient to climate change	Develop and enforce regulations to reduce emissions of air pollutants from traffic, industry, and other sources Incentive programs to increase energy efficiency
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	Alter health data collection systems	Alter health data collection systems	Enhance vector surveillance and	Enhance surveillance and monitoring	Enhance health data collection

Monitoring	to monitor for increased morbidity and mortality during a heatwave	to monitor for disease outbreaks during and after an extreme event	control programs Monitor disease occurrence	programs for waterborne diseases	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			

An additional category of measures includes public education and outreach programs 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 6 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).

Box 6: 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

3.6 Conclusions

The health impacts projected with climate change means there is a need to strengthen and improve programs and activities aimed at reducing the risks of climate-sensitive health determinants and outcomes. 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 where gaps in adaptive capacity have not or are not being addressed.

Because of regional variability in the types of climate change attributable health stressors and associated responses, it is difficult to generally summarize adaptation at the national level. This difficulty is compounded by the fact that there is no central (or regional) agency responsible for adaptation. The elements needed, from weather forecasting to air and water quality regulations to vector control programs to disaster response, are spread across multiple agencies and organizations, with inconsistent collaboration. Public health adaptation will be facilitated by identifying and supporting a lead agency that can provide access to the information and tools needed for a particular adaptation measure, and that can support the adaptation process. Having a central agency that communities and states can call when they have questions about adaptation would be extremely beneficial and efficient. One model is the UK Climate Impacts Programme, funded by the UK government to provide downscaled climate projections and help the commercial and public sectors assess their vulnerability to climate change so that they can adapt effectively (http://www.ukcip.org.uk/). They bring together people from the private and public sectors with a shared interest, such as being in the same region or working in a particular sector, and support the adaptation process. The findings are used by the UK government's lead agency on climate change to inform policy.

Another model is the NOAA Regional Integrated Sciences and Assessments (RISA) program (http://www.climate.noaa.gov/cpo_pa/risa/). RISA centers have been funded in eight regions (five in Alaska and the West, the Pacific, the Southeast, and the Carolinas) that support research to address climate-sensitive issues of concern to regional decisionmakers and policy planners. These programs primarily focus on fisheries, water, wildfire, and agriculture, with limited focus on public health.

Overall, the U.S. has high capacity to cope with the projected health impacts of climate change. However, 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.

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Synthesis and Assessment Product 4.6

Chapter 4

Effects of Global Change on Human Settlements

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4.1 Introduction

Human settlements are where people live; so effects of climate change on settlements are directly relevant to human well-being. This chapter briefly summarizes current knowledge about climate change vulnerabilities and impacts in human settlements in the United States, potentials for adaptation to climate change in U.S. settlements, conclusions and recommendations based on what is currently known, and research needs to improve the available knowledge.

As such recent events as Hurricane Katrina in 2005 and electric power outages during the hot summer of 2006 have demonstrated dramatically, climate can affect U.S. cities and smaller settlements. Settlements, and in particular larger urban areas, have often been the focus of human efforts to control exposures to climate and other manifestations of nature, reducing their importance in our everyday lives as we live and work inside climate-controlled structures, surrounded by natural features that are engineered to fit our convenience.

But it has been sobering to find that even the world's most advanced societies cannot ignore climate, even in built areas. Climate affects the costs of assuring comfort at home and work for the affluent and, for the poor, levels of comfort in terms of temperature and humidity. Climate provides inputs for a good life: water, products and services from agriculture and forestry, pleasures and tourist potentials from nature, biodiversity, and outdoor recreation. Climate affects the presence and spread of diseases and other health problems, and it is associated with threats from natural disasters: floods, fires, droughts, wind, hail, ice, heat, and cold waves. If the climate is changing, therefore, then that is important news for U.S. settlements.

Certain kinds of circumstances are likely to cause particular concerns for cities and towns in the United States as they consider possible implications of climate change. For instance, some settlements are located in especially vulnerable areas, such as on or near coasts subject to storms and sea-level rise. Some have economies linked to economic sectors especially sensitive to climate variation, such as agriculture or tourism. Some settlements are already stressed by other forces that might interact with climate change effects, such as rapid population growth, aging physical infrastructures, poverty, and social friction. Some are considerably dependent on linkage systems, such as bridges or electric power lines, which could be vulnerable to impacts of climate change.

On the other hand, some U.S. settlements may find opportunities in climate change. Warmer winters are not necessarily undesirable. Periods of change tend to reward progressive, well-governed communities. Considering climate change effects may help to focus attention on other important issues for the long-term sustainable development of settlements and communities. In many regards, U.S. cities and counties – along with some U.S. states – have been more active in considering climate change as a policy issue than has been the case at the national level, not because they are required to do so by national policy but because they choose to do so in order to respond to local driving forces. In particular, larger settlements are sometimes more aware of their roles as emitters of greenhouse gases, and therefore a part of the causes of climate change, than of their possible vulnerabilities to impacts (see Potentials for Adaptation to Climate Change, below). Furthermore, planning for the future is an essential part of public policy decision-making in urban areas. Since infrastructure investments in urban areas are often both large and difficult to reverse, climate considerations are increasingly perceived as one of a number of relevant issues to consider when planning for the future (Ruth, 2006a). If U.S. settlements, especially larger cities, respond effectively to climate change concerns, their actions could have far-reaching implications for human well-being, because these areas are where most of the U.S. population lives, large financial decisions are made, political influence is often centered, and many technological and social innovations take place.

Meanwhile, our pattern of human settlement in the U.S. is changing. Besides shifts of population from frost-belt to sun-belt settlements, patterns are changing in other ways as well. For instance, what once appeared to be an inexorable spread of households from urban centers to peripheries is showing renewal in many city centers as metropolitan areas continue to expand across multiple jurisdictions (Solecki and Leichenko, 2006). And modern information technologies are enabling people to perform what were historically urban functions from relatively remote locations. Assessing effects of climate change on human settlements in the U.S. is complicated by the fact that we are changing in our settlement patterns and preferences.

These are important questions for both our settlements and the nation as a whole, but the ability to illuminate the issues is severely limited by the fact that little research has been done to date specifically on effects of climate change on U.S. cities and towns. Reasons appear to include (a) a general lack of support for climate change impact research, compared with climate system and mitigation research, (b) limitations in capacities to project climate change impacts at the geographic scale of a metropolitan area (or smaller), and (c) the fact that none of the federal agencies currently active in climate science research has a clear responsibility for settlement impact issues. To some degree, gaps can be filled by referring to several comprehensive analyses that do exist, to literature on effects of climate *variation* on settlements and their responses, to research on climate change impacts on cities in other parts of the world, and to analogs from the U.S. historical experience with responses of urban areas to significant environmental changes (see Box: U.S. Urban Responses to Environmental Change: A Historical Perspective). But this is little more than a place to start.

Whatever the reasons, the current knowledge base provides only a shaky basis for developing conclusions and recommendations at this time. In many cases, the best that can be done right now is to sketch out the landscape of issues that should be considered by both urban decision-makers and the research community as a basis for further discussion, offering illustrations from the relatively small research literature that is now available.

4.2 Climate Change Vulnerabilities and Impacts in Human Settlements

Consider first the possible impacts of climate change on settlements in the U.S., what determines the vulnerability of a particular settlement to such impacts, and how the impacts could affect our settlement patterns and various systems related to those patterns.

Determinants of vulnerabilities/impacts

In many cases, it has been difficult to project impacts of climate change on human settlements in the U..S., in part because climate change forecasts are not specific enough for the scale of settlement decision-making (as for other relatively local-scale impact questions) but more profoundly because climate change is not the only change being confronted by settlements. More often, attention is paid to vulnerabilities to climate change, if those changes should occur.

(1) Vulnerabilities to or opportunities from climate change are related to three factors, both in absolute terms and in comparison to other areas (Clark et al., 2000): Exposure to climate change. To what climate changes is a place likely to be exposed: temperature or precipitation changes, changes in storm exposures and/or intensities, changes in the sea level?

(2) Sensitivity to climate change. If primary climate changes were to occur, how sensitive are the activities and populations of a settlement to those changes. For instance, a city dependent substantially on a regional agricultural or forestry economy, or to the availability of abundant water resources, might be considered more sensitive than a city whose economy is based mainly on an industrial sector less sensitive to climate variations.

(3) Coping capacity. Finally, if effects are experienced due to a combination of exposure and sensitivity, how able is a settlement to handle those impacts without disabling damages, perhaps even with new opportunities?

At the current state of knowledge, vulnerabilities to possible impacts (including possible opportunities as well as possible costs, despite the negative implications of the term “vulnerability”) are easier to project than actual impacts because they *estimate risks or opportunities* associated with possible consequences rather than *estimating the consequences* themselves. And vulnerabilities are shaped not only by existing exposures, sensitivities, and coping capacities but also by the ability of settlements to develop adaptive responses to risks (see Adaptation below).

U.S. URBAN RESPONSES TO ENVIRONMENTAL CHANGE: A HISTORICAL PERSPECTIVE

Over time, American cities have been affected in many ways by environmental change and environmental events. Anthropogenic actions or beliefs, however, in many cases shaped the severity of the environmental impacts. Founders of cities often evidenced a lack of care in regard to their sitting, focusing on the positive aspects of a location such as commercial or recreational possibilities or the availability of a precious mineral but ignored risks such as flooding potential, limited water, food or fuel supplies, or the presence of health threats. Oftentimes urbanites severely exploited their environments, polluting ground water and adjacent water bodies, building in unsafe and fragile locations, changing landforms, and filling in wetlands. Construction of the urban built environment involved vast alterations in the landscape, as forests and vegetation and wildlife species were eliminated and replaced by highways, suburbs, and shopping malls. The building of wastewater and water supply systems had the effect of altering regional hydrology, creating large vulnerabilities. Still other cases of the disregarding of environmental risk to cities involved sets of beliefs such as the weather was changing permanently for the good, technology could solve problems, or new resources could be discovered.

The response of many cities to environmental change and increases in environmental risk was to seek ways to modify or control environmental events using technology. Cities exposed to flooding built levees and seawalls and channelized rivers. When urbanites depleted and polluted local water supplies cities went outside their boundaries to seek new supplies. building reservoirs, aqueducts, and creating protected watersheds. When urban consumption exhausted local fuel sources, cities adapted to new fuels, embraced new technologies, or searched far beyond city boundaries for new supplies. Many of these actions resulted in the extension of the urban ecological footprint, so that urban growth and development impacted not only the urban site but also increasingly the urban hinterland and beyond.

There are few examples of environmental disasters or climate change actually resulting in the abandonment of an urban site. One case appears to be that of the Hohokam Indians of the Southwest, who built extensive irrigation systems, farmed land, and built large and dense settlements over a period of approximately 1,500 years.   Yet, they abandoned their settlements and disappeared into history. The most prominent explanation for their disappearance is an ecological one - that the Hohokam irrigation systems suffered from salinization and water logging, eventually making them unusable. Other factors besides the ecological ones may have also entered into the demise of their civilization and abandonment of their cities, but the ecological explanation appears to have the most supporters.

In the case of America in the 19th and 20th centuries, however, no city has been abandoned because of environmental or climatic factors. Galveston, Texas suffered from a catastrophic tidal wave but still exists as a human settlement, now protected by a extensive sea wall. Johnstown, Pennsylvania has undergone major and destructive flooding since the late 19th century, but continues to survive as a small city. Los Angeles and San Francisco, are extremely vulnerable to earthquakes, but still continue to increase in population. And, in coming years New Orleans almost certainly will experience a hurricane as or more severe than Katrina, and yet rebuilding goes on, encouraged by the belief that technology will protect it in the future. Whether or not ecological disaster or extreme risk will eventually convince Americans to abandon their cities, as the Hohokam did, has yet to be determined.

Projected impacts of climate change on settlements in the U.S

Possible impacts of climate change on settlements in the U.S. are usually assessed by projecting climate changes at a regional scale: temperature, precipitation, severe weather events, and sea level rise. Ideally, these regional projections are at a relatively detailed scale, and ideally they consider seasonal as well as annual changes and changes in extremes as well as in averages; but these conditions cannot always be met.

The most comprehensive assessments of possible climate change impacts on settlements in the U.S. have been two studies of major metropolitan areas:

(1) New York: The first U.S. *National Assessment of Potential Consequences of Climate Variability and Change*, often referred to as "The National Assessment" (NACC, 2000) included twenty "regional assessments," one of which was specifically designed to examine possible consequences for a large metropolitan area: the "Metropolitan East Coast," essentially the New York city area (Rosenzweig and Solecki, 2001a; also see Rosenzweig and Solecki, 2001b, and Solecki and Rosenzweig, 2006). This assessment concluded that impacts of climate change on this metropolitan area are likely to primarily negative over the long term, with potentially significant costs increasing as the magnitude of climate change increases, although there are substantial uncertainties.

(2) Boston: A later study considered Climate's Long-term Impacts on Metro Boston (CLIMB), focused on possible interactions between climate change and infrastructure systems and services in the Boston area, along with integrated impact and response strategies (Kirshen *et al.*, 2004; also see Kirshen *et al.*, 2006 and forthcoming). This study concluded that long-term impacts of climate change are likely to depend at least as much on behavioral and policy changes over this period as on temperature and other climate changes.

Other U.S. studies include Seattle (Hoo and Sumitani, 2005) and Los Angeles (Koteen *et al.*, 2001) (Table 1). Internationally, studies have included several major metropolitan areas, such as London (London Climate Change Partnership, 2004) and Mexico City (Molina *et al.*, 2005) as well as possible impacts on smaller settlements (e.g., AIACC: see www.aiaccproject.org). A relevant historical study of effects of an urban heat wave in the U.S. is Klinenberg, 2003.

Vulnerabilities of settlements to impacts of climate change vary regionally (see Box and Vignettes below), but they generally include some or many of the following impact concerns:

1 *Effects on health*. It is well-established that higher temperatures in urban areas are related to higher concentrations of ozone, which in turn cause respiratory problems. There is also some evidence that combined effects of heat stress and air pollution may be greater than simple additive effects (Patz and Balbus, 2001). Moreover, historical data show relationships between mortalities and temperature extremes (Rozenzweig and Solecki, 2001a). Other health concerns include changes in exposure to water and food-borne diseases, vector-borne diseases, concentrations of plant species associated with allergies, and exposures to extreme weather events such as storms, floods, and fires (see health chapter of SAP 4.6).

2 *Effects on water and other urban infrastructures*. Changes in precipitation patterns may lead to reductions in meltwater, river flows, groundwater levels, and in coastal areas lead to saline intrusion in rivers and groundwater, affecting water supply; and warming may increase water demands (Kirshen, 2002; Ruth *et al.*, forthcoming). Moreover, storms, floods, and other severe weather events may affect other infrastructures such as sanitation, transportation, supply lines for food and energy, and communication. Exposed structures such as bridges and electricity transmission networks are especially vulnerable. In many cases, infrastructures are interconnected; an impact on one can also affect others (Kirshen, *et al.*, forthcoming). An example is an interruption in energy supply, which increases heat stress for vulnerable populations (Ruth *et al.*, 2006a).

3 *Effects of severe weather events*. Clearly, settlements in risk-prone regions have reason to be concerned about severe weather events, ranging from severe storms combined with sea-level rise in coastal areas to increased risks of fire in drier arid areas. Vulnerabilities may be especially great for rapidly-growing and/or larger metropolitan areas, where the potential magnitude of both impacts and coping requirements could be very large (IPCC, 2001b).

4 *Effects on energy requirements*. Warming is virtually certain to increase energy demand in U.S. cities for cooling in buildings while it reduces demands for heating in buildings (see SAP 4.5). Demands for cooling during warm periods could jeopardize the reliability of service in some regions by exceeding the supply capacity, especially during periods of unusually high temperatures (see Vignette below). Higher temperatures also affect costs of living and business operation by increasing costs of climate control in buildings (Amato *et al.*, 2005; Ruth and Lin, 2006c; Kirshen *et al.*, forthcoming).

5 *Effects on the urban metabolism*. An urban area is a living complex mega-organism, associated with a host of inputs, transformations, and outputs: heat, energy, materials, and others (Decker *et al.*, 2000). An example is the Urban Heat Index (UHI), which measures the degree to which built/paved areas are associated with higher temperatures than surrounding rural areas (see box: Climate Change Impacts on he Urban Heat Island Effect (UHI)). Imbalances in the urban metabolism can aggravate climate change impacts, such as roles of UHI in the formation of smog in cities.

Table 1. Overview of Integrated Assessments of Climate Impacts and Adaptation in U.S. Cities

	Bloomfield *et al.*, 1999	**Kooten *et al.*, 2001**	**Rosenzweig *et al.*, 2000**	**Kirshen *et al.*, 2004**	**Hoo and Sumitani, 2005**
Location:	Greater Los Los Angeles	New York	Metropolitan New York	Metropolitan Boston	Metropolitan Seattle
Coverage:					
Water supply	X	X	X	X	
Water Quality				X	
Water Demand				X	
Sea-level Rise	X		X	X	X
Transportation				X	X
Communication					
Energy			X	X	
Public Health					
Vector-borne Diseases					
Food-borne Diseases		X			
Temperature-related Mortality				X	
Temperature-related Morbidity	X	X			
Air-quality Related Mortality					
Air-quality Related Morbidity			X		
Oher	X	X	X		
Ecosystems					
Wetlands					
Other (Wldfires)	X		X		
Urban Forests (Trees and Vegetation)		X			
Air Quality		X			X
Extent of:					
Quantitative Analysis	Low	Medium	Medium	High	Low
Computer-based Modeling	None	Low	Low	High	None
Scenario Analysis	None	None	Medium	High	Medium
Explicit Risk Analysis	None	None	None	Medium	None
Involvement of:					
Local Planning Agencies	None	None	High	High	High
Local Government Agencies	None	None	High	High	High
Private Industry	None	None	None	Low	None
Non-profits	None	None	Low	High	None
Citizens	None	None	None	Medium	None
Identification of:					
Adaptation Options	X	X	X	X	X
Adaptation Cost			X	X	
Extent of Integration Across Systems	None	None	Low	Medium	Low
Attention to Differential Impacts (e.g., on individual types of businesses, specific sub-populations)	None	None	Low	Low	Low

Table 2. Regional vulnerabilities of settlements to impacts of climate change in the United States.

REGIONAL VULNERABILITIES OF SETTLEMENTS TO IMPACTS OF CLIMATE CHANGE

Region	Vulnerabilities	Major Uncertainties
Metro NE	Flooding, infrastructures, health, water supply, sea-level rise	Storm behavior, precipitation
Larger NE	Changes in local landscapes, tourism, water, energy needs	Ecosystem impacts
Mid-Atlantic	Multiple stresses	Ecosystem impacts
Coastal SE	More intense storms, sea-level rise, flooding, heat stress	Storm behavior, coastal land use, sea-level rise
Inland SE	Water shortages, heat stress, UH1, economic impacts	Precipitation change, development paths
Upper Midwest	Lake and river levels, extreme weather events, health	Precipitation change, storm behavior
Inner Midwest	Extreme weather events, health	Storm behavior
Appalachians	Ecological change, reduced demand for coal	Ecosystem impacts, energy policy impacts
Great Plains	Water supply, extreme events, stresses on communities	Precipitation changes, weather extremes
Mountain West	Reduced snow, water shortages, fire, tourism	Precipitation changes, effects on winter snowpack
Arid Southwest	Water shortages, fire	Development paths, precipitation changes
California	Water shortages, heat stress	Temperature and precipitation changes, infrastructure impacts
Northwest	Water shortages, ecosystem stresses, coastal effects	Precipitation changes, sea-level rise
Alaska	Effects of warming, vulnerable populations	Warming, sea-level rise
Hawaii	Storms and other weather extremes, freshwater supplies, health	Storm behavior, precipitation change

6 *Effects on economic competitiveness, opportunities, and risks.* Climate change has the potential not only to affect settlements directly but also to affect them through impacts on other areas linked to their economies at regional, national, and international scales (Rosenzweig and Solecki, 2006). In addition, it can affect a settlement's economic base if it is sensitive to climate, as in areas where settlements are based on agriculture, forestry, water resources, or tourism (IPCC, 2001b).

7 *Effects on social and political structures.* Climate change can add to stress on social and political structures by increasing management and budget requirements for public services such as public health care, disaster risk reduction, and even public security. As sources of stress grow and combine, the resilience of social and political structures that are already somewhat shaky is likely to suffer, especially in areas with relatively limited resources (Sherbinin *et al.*, 2006). *Especially vulnerable populations (also see Quality of Life* chapter of SAP 4.6*).* Where climate change adds to stress levels in settlements, it is likely to be especially problematic for vulnerable parts of the population: the poor, the elderly, those already in poor health, the disabled, those living alone, those with limited rights and power (e.g., recent in-migrants with limited English skills), and/or indigenous populations dependent on one or a few resources. As one example, warmer temperatures in urban summers have a more direct impact on populations who live and work without air-conditioning. Implications for environmental justice are clear; see, for instance, Congressional Black Caucus Foundation, 2004.

8 *Effects of sea level rise.* Approximately half of the U.S. population, 160 million people, will live in one of 673 coastal counties by 2008 (NOAA, 2005). Obviously, settlements in coastal areas – particularly on gently-sloping coasts – should be concerned about sea level rise in the longer term, especially if they are subject to severe storms and storm surges and/or if their regions are showing gradual land subsidence (Neumann *et al.*, 2000; Kirshen *et al.*, 2004).

In general, however, climate change effects on human settlements in the U.S. are imbedded in a variety of complexities that make projections of quantitative impacts over long periods of time very difficult. For instance, looking out over a period of many decades, it seems likely that other kinds of change – such as technological, economic, and institutional – will have more impact on the sustainability of most settlements than climate change per se (IPCC, forthcoming). Climate change will interact with other processes, driving forces, and stresses; and its significance, positive or negative, will largely be determined by these interactions. It is therefore difficult to assess effects of climate change without a reasonably clear picture of future scenarios for these other processes, which are usually not available.

VIGNETTES OF VULNERABILITY - I

Alaskan settlements

Human settlements in Alaska are already being exposed to impacts from global warming (ACIA, 2004), and these impacts are expected to increase. Many coastal communities see increasing exposure to storms, with significant coastal erosion, and in some cases facilities are being forced either to relocate or to face increasing risks and costs. Thawing ground is beginning to destabilize transportation, buildings, and other facilities, posing needs for rebuilding, with ongoing warming adding to construction and maintenance costs. And indigenous communities are facing major economic and cultural impacts. One recent estimate of the value of Alaska's public infrastructure at risk from climate change set the value at tens of billions of today's dollars by 2080, with the replacement of buildings, bridges, and other structures with long lifetimes having the largest public costs (Larsen *et al.*, 2007).

Coastal SE settlements

Recent hurricanes striking the coast of the U.S. Southeast cannot be attributed clearly to climate change, but if climate change increases the intensity of storms as projected (IPCC, 2001b; Emanuel, 2005) that experience suggests a range of possible impacts. Consider, for example, the case of Hurricane Katrina (IPCC, forthcoming). In 2005, the city of New Orleans had a population of about half a million, located on the delta of the Mississippi River along the U.S. Gulf Coast. Urban development throughout the 20^{th} Century has significantly increased land use and settlement in areas vulnerable to flooding, and a number of studies had indicated growing vulnerabilities to storms and flooding. In late August 2005, Hurricane Katrina moved onto the Louisiana and Mississippi coast with a storm surge, supplemented by waves, reaching up to 8.5 m above sea level. In New Orleans, the surge reached around 5m, overtopping and breaching sections of the city's 4.5m defenses, flooding 70 to 80 % of New Orleans, with 55 % of the city's properties inundated by more than 1.2 m and maximum flood depths up to 6 m. 1101 people died in Louisiana, nearly all related to flooding, concentrated among the poor and elderly. Across the whole region, there were 1.75 million private insurance claims, costing in excess of $40 billion (Hartwig, 2006), while total economic costs are projected to be significantly in excess of $100 billion. Katrina also exhausted the federally backed National Flood Insurance Program (Hunter, 2006), which had to borrow $20.8 billion from the Government to fund the Katrina residential flood claims. In New Orleans alone, while flooding of residential structures caused $8-$10 billion in losses, $3-6 billion was uninsured. 34,000-35,000 of the flooded homes carried no flood insurance, including many that were not in a designated flood risk zone (Hartwig, 2006). Six months after Katrina, it was estimated that the population of New Orleans was 155,000, with the number projected to rise to 272,000 by September 2008 – 56% of its pre-Katrina level (McCarthy *et al*., 2006).

VIGNETTES OF VULNERABILITY – II

Arid Western settlements

Human settlements in the arid West are affected by climate in a variety of ways, but perhaps most of all by water scarcity and risks of fire. Clearly, access to water for urban populations is sensitive to climate, although the region has developed a vast system of engineered water storage and transport facilities, associated with a very complex set of water rights laws (NACC, 2001). It is very likely that climate change will reduce winter snowfall in the West, reducing total runoff – increasing spring runoff while decreasing summer water flows. Meanwhile, water demands for urban populations, agriculture, and power supply are expected to increase. If total precipitation decreases or becomes more variable, extending the kinds of drought that have affected much of the interior West in recent years, water scarcity will be exacerbated, and increased water withdrawals from wells could affect aquifer levels and pumping costs. Moreover, drying increases risks of fire, which have threatened urban areas in California and other Western areas in recent years. The five-year average of acres burned in the West is more than 5 million, and urban expansion is increasing the length of the urban-wildlands interface (Morehouse *et al.*, 2006).

Summer 2006 Heat Wave

In July and August 2006, a severe heat wave spread across the United States, with most parts of the country recording temperatures well above the average for that time of the year. For example, temperatures in California were extraordinarily high, setting records as high as 130 degrees. As many as 225 deaths were reported by press sources, many of them in major cities such as New York and Chicago. Electric power transformers failed in several areas, such as St. Louis and Queens New York, causing interruptions of electric power supply, and some cities reported heat-related damages to water lines and roads. In many cities, citizens without home air-conditioning sought shelter in public and office buildings, and city/county health departments expressed particular concern for the elderly, the young, pregnant women, and individuals in poor health. Although this heat wave cannot be attributed directly to climate change, it suggests a number of issues for human settlements in the U.S. as they contemplate a prospect of temperature extremes in the future that are higher and/or longer-lasting than historical experience.

CLIMATE CHANGE IMPACTS ON THE URBAN HEAT ISLAND EFFECT (UHI)

Climate change impacts on the Urban Heat Island (UHI) effect will primarily depend upon the geographic location of a specific city, its urban morphology (i.e. landscape and built-up characteristics), and areal extent (i.e., overall spatial “footprint”). These factors will mitigate or exacerbate how the UHI phenomenon (Figure 2) is affected by climate change, but overall, climate change will most likely impact the UHI effect in the following ways:

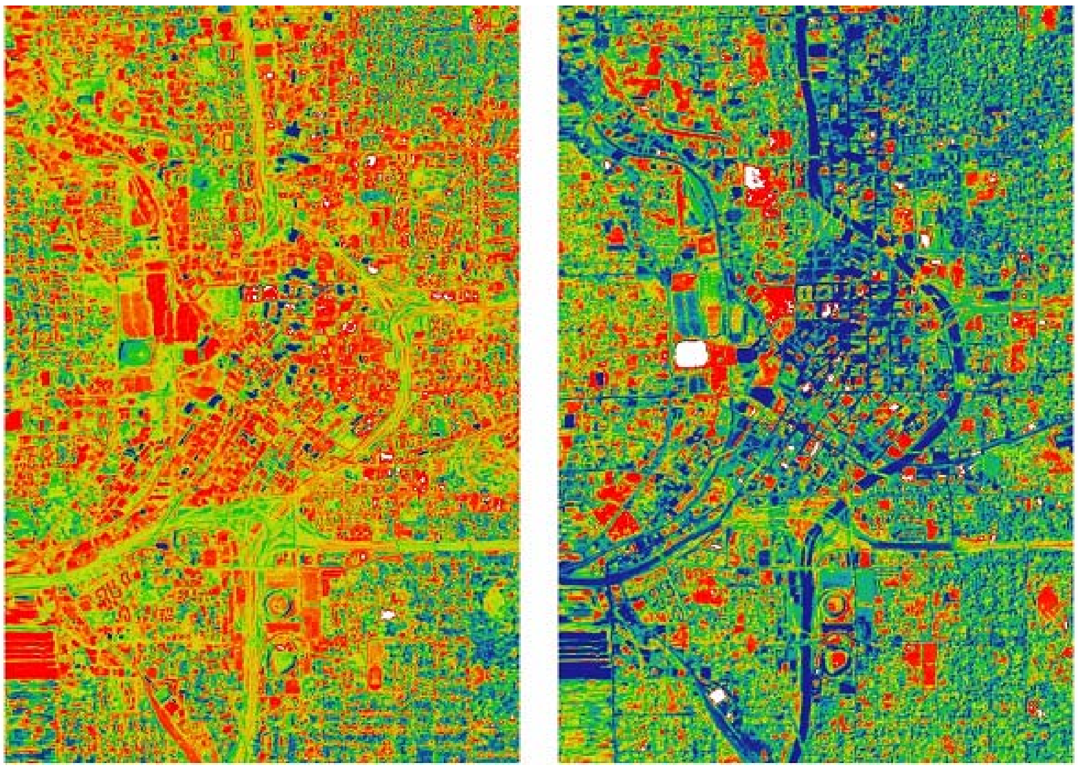

Figure 2. Example of urban surface temperatures and albedo for the Atlanta, Georgia Central Business District (CBD) area derived from high spatial resolution (10m) aircraft thermal remote sensing data. The image on the left illustrates daytime surface heating for urban surfaces across the CBD. White and red colors indicate very warm surfaces (~40-50ºC). Green relates to surfaces of moderately warm temperatures (~25-30ºC). Blue indicates cool surfaces (e.g., vegetation, shadows) (~15-20ºC). Surface temperatures are reflected in the albedo image on the right where warm surfaces are dark (i.e., low reflectivity) and cooler surfaces are in red and green (i.e., higher reflectivity). The images exemplify how urban surface characteristics influence temperature and albedo as drivers of the urban heat island effect (Quattrochi et al., 2000).

- Exacerbation of the intensity and areal extent of the UHI as a result of warmer surface and air temperatures along with the overall growth of urban areas around the world. Additionally, as urban areas grow and expand, there is a propensity for lower albedos which forces more a more intense UHI effect. (There is also some indication that sustained or prolonged higher nighttime air temperatures over cities that may result from warmer global temperatures will have a more significant impact on humans than higher daytime temperatures.)

- As the UHI intensifies and increases, there will potentially be a subsequent impact on deterioration of air quality, particularly on ground level ozone caused by higher overall air temperatures and an increased background effect produced by the UHI as an additive air temperature factor that helps to elevate ground level ozone production. Additionally, particulate matter ($PM_{2.5}$) will potentially increase due to a number of human induced and natural factors (e.g., more energy production to support higher usage of air conditioning).

CLIMATE CHANGE IMPACTS ON THE URBAN HEAT ISLAND EFFECT (UHI) -- continued

- The UHI has an impact on local meteorological conditions by forcing rainfall production either over, or downwind, of cities. As the UHI effect intensifies, there will be a higher probability for urban-induced rainfall production (dependent upon geographic location) with a subsequent increase in urban runoff and flash flooding.

- Exacerbation and intensification of the UHI will have impacts on human health:

  - increased incidence of heat stress
  - impact on respiratory illnesses such as asthma due to increases in particulate matter caused by deterioration in air quality as well as increased pollination production because of earlier pollen production from vegetation in response to warmer overall temperatures

(Lo and Quattrochi, 2003; Brazel and Quattrochi, 2006; Ridd, 2006; Stone, 2006)

In many cases, these interactions involve not only direct impacts such as warming or more or less precipitation but, sometimes more important, second, third, etc. order impacts, as direct impacts cascade through urban systems and processes (e.g., warming which affects urban air pollution which affects health which affects public service requirements which affects social harmony: Kirshen *et al*., forthcoming). Some of these higher-order impacts, in turn, may feed back to create ripple effects of their own. For example, a heat wave may trigger increased energy demands for cooling, which may cause more air conditioners and power generators to be operated, which could lead to higher urban heat island effects, inducing even higher cooling needs.

Besides such a "multi-stress" perspective, it is highly likely that effects of climate change on settlements is shaped by certain "thresholds," below which effects are not major but where effects rather quickly become major because some kind of limiting point is reached. An example might be a city's capacity to cope with sustained heat stress of with a natural disaster. In general, these climate-related thresholds for human settlements in the U.S. are not well-understood.

But for either multi-stress assessments of threshold analyses, changes in climate <u>extremes</u> are very often of more concern than changes in climate <u>averages</u>. Besides extreme weather events, such as hurricanes or tornadoes, ice storms, winds, heat waves, drought, or fire, settlements may be affected by changes in daily or seasonal high or low levels of temperature or precipitation, which are seldom projected by climate change models (see Figure 1).

Finally, human settlements may be affected by climate change <u>mitigation</u> initiatives as well as by climate change itself. Examples could include effects on policies related to energy sources and uses, environmental emissions, and land use (see Adaptation below). The most direct and short-term effects would likely be on settlements in regions whose economies are closely related to the production and consumption of large quantities of fossil fuels. Indirect and longer

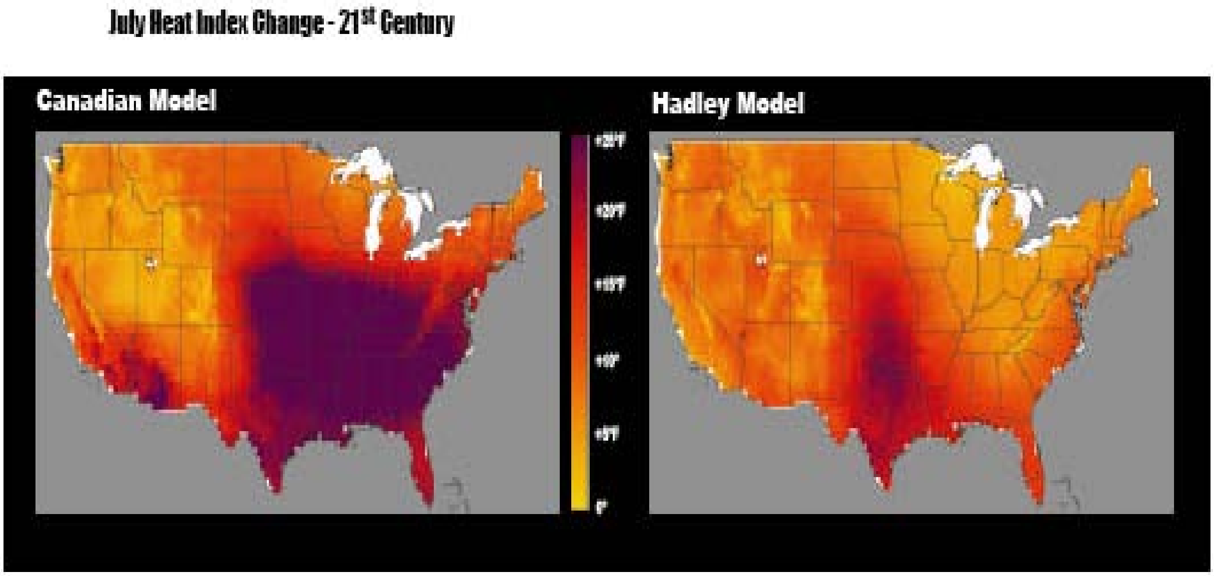

Figure 1. The U.S. National Assessment (NACC, 2001) projected changes in the July heat index for regions of the U.S. For the already hot and humid Southeast, for instance, the UK Hadley model suggested increases of 8 to 15 degrees F. for the southern-most states, while the Canadian model projected increases above 20 degrees for much of the region.

term effects are less predictable . At the same time, climate change can have positive as well as negative implications for settlements. Examples of possible positive effects include:

(1) Reduced winter weather costs and stresses. Warmer temperatures in periods of the year that are normally cold are not necessarily undesirable. They reduce cold-related stresses and costs (e.g., costs of warming buildings and costs of clearing ice and snow from roads and streets), particularly for cold-vulnerable populations. They expand opportunities for warmer-weather recreational opportunities over larger parts of the year, and they expand growing seasons for crops, parks, and gardens.

(2) Increased attention to long-term sustainability. One of the most positive aspects of a concern with climate change can be that it stimulates a broader discussion of what sustainability means for a city or smaller settlement (Wilbanks, 2003; Ruth, 2006). Even if climate change itself may not be the most serious threat to

sustainability, considering climate change impacts in a multi-change, multi-stage context can encourage and facilitate processes that lead to progress in dealing with other sources of stress as well.

(3) Improved competitiveness compared with settlements subject to more serious adverse impacts. While some settlements may turn out to be "losers" due to climate change impacts, for instance related to perceptions of increased storm risks or effects on tourism, others may be "winners," as changes in temperature or precipitation result in added economic opportunities (see the following section). In addition for many settlements climate change can be an opportunity not only to compare their net impacts with others, seeking advantages as a result, but to present a progressive image by taking climate change (and related sustainability issues) seriously. Examples might include cities in the border south who try to persuade prospective sun-belt retirees that locations farther south, especially in coastal locations, could be too hot or too storm-prone to be good places to move, or settlements in some sections of the northern part of the country who make a case that reduced costs for winter heating are greater than increased costs for summer cooling.

Possible effects on U.S. settlement patterns and characteristics

As climate change affects individual settlements in the U.S., large and small, those changes are likely to have effects on population patterns involving hosts of settlements at regional and national scales, in combination with other driving forces (even if other forces are often more important, such as demographic changes). Most of the possible effects are linked with changes in regional comparative advantage, with consequent migration of population and economic activities (Ruth and Coelho, forthcoming).

Examples of such possible issues include:

(1) Particular regional risks. It is likely that regions exposed to risks from climate change will see a movement of population growth and economic activity to other locations. One reason is public perceptions of risk, but a more powerful driving force may be the availability of insurance. The insurance sector is one of the most adaptable of all economic sectors, and its exposure to costs from severe storms and other extreme weather events is likely to lead it to withdraw (or to make much more expensive) private insurance coverage from areas vulnerable to climate change impacts (IPCC, forthcoming), which would encourage both businesses and individual citizens to consider other locations over a period of several decades.

(2) Areas whose economies are linked with climate-sensitive resources or assets. Settlements whose economic bases are related to such sectors as agriculture, forestry, tourism, water availability, or other climate-related activities could be affected either positively or negatively by climate change, depending partly on the

adaptability of those sectors (i.e., their ability to adapt to changes without shifting to different locations).

(3) Shifts in the comparative cost structure of climate control. Related to a range of possible climate change effects – higher costs for space cooling in warmer areas, higher costs of water availability in drier areas, more or less exposure to storm impacts in some areas, and sea level rise – regions of the U.S. and their associated settlements are likely to see gradual changes over the long term in their relative attractiveness for a variety of human activities. One example, although its likelihood is highly uncertain, would be a gradual migration of the "Sun Belt" northward, as retirees and businesses attracted by environmental amenities find that regions less exposed to very high temperatures and seasonal major storms are more attractive as places to locate.

(4) Changes in regional comparative advantage related to shifts in energy resource use. If climate mitigation policies result in shifts from coal and other fossil resources toward non-fossil energy sources, or if climate changes affect the prospects of renewable energy sources (especially hydropower), regional economies related to the production and/or use of energy from these sources could be affected, along with regional economies more closely linked with alternatives.

(5) Urban "footprints" on other areas. Resource requirements for urban areas involve larger areas than their own bounded territories alone, and ecologists have sought to estimate the land area required to supply the consumption of resources and compensate for emissions and other wastes from urban areas (e.g., Folke *et al.*, 1997). By possibly affecting the sizes and patterns of settlements, along with the resource capacities of source areas for their inputs and destinations of their outputs, climate change could affect the nature, size, and geographic distribution of these footprints.

As one example, no other region in the U.S. is likely to be as profoundly changed by climate change as Alaska, our nation's part of the polar region of Earth. Because warming is more pronounced closer to the poles, and because settlement and economic activities in Alaska have been shaped and often constrained by Arctic conditions, in this region warming is especially likely to reshape patterns of human settlement.

Besides impacts on built infrastructures designed for permafrost foundations and effects on indigenous societies (see Vignette above), many observers expect warming in Alaska to stimulate more active oil and gas development (and perhaps other natural resource exploitation), and if thawing of Arctic ice permits the opening of a year-round Northwest sea passage it is virtually certain that Alaska's coast will see a boom in settlements and port facilities (ACIA, 2004).

Possible effects on other systems linked with settlements

Human settlements are foci for many economic, social, and governmental processes, and we know from historical experience that catastrophes in cities can have significant economic, financial, and political effects much more broadly.
The case which has received the most attention to date is insurance and finance (IPCC, forthcoming). Other cases of possible ripple effects are on media and other information/communications sources, often city-focused, whose messages are affected by the personal experiences of those who are their purveyors.
Most importantly, perhaps, in a one-person/one-vote democratic process in an urbanizing country, the politics of responses to climate change concerns will depend considerably on the experiences and viewpoints of urban dwellers.

4.3 Potentials for Adaptation to Climate Change in Human Settlements

Settlements are important in considering prospects for adaptation to climate change, both because they represent concentrations of people and because buildings and other engineered infrastructures are ways to manage risk and monitor/control threats associated with climate extremes and other effects, such as disease vectors.

Where climate change might present risks of adverse impacts for U.S. settlements and their populations, there are two basic alternatives to respond to such concerns (a third is combining the two). One response is to contribute to climate change mitigation strategies, i.e., by taking actions to reduce their greenhouse gas emissions and by showing leadership in encouraging others to support such actions (see Box: Roles of Settlements in Climate Change Mitigation). The second response is to consider strategies for adaptation to the changes, i.e., finding ways either to reduce sensitivity to projected changes or to increase the settlement's coping capacities. Adaptation can rely mainly on anticipatory actions to avoid damages and costs, such as "hardening" coastal structures to sea-level rise; and/or adaptation can rely mainly on response potentials, such as emergency preparedness; or it can include a mix of the two approaches. Research to date suggests that anticipatory adaptation may be more cost-effective than reactive adaptation (Kirshen *et al.*, 2004).

Adaptation could be important to the well-being of U.S. settlements as climate change emerges over the next century. As just one example, the New York climate impact assessment (Rosenzweig and Solecki, 2001a) projects significant increases in heat-related deaths based on historical relationships between heat stress and mortality, while the Boston CLIMB assessment (Kirshen *et al.*, 2004) projects that, despite similar projections of warming, heat-related deaths will decline over the coming century because of adaptation (See section 3.5). Whether or not adaptation to climate change occurs in U.S. cities is therefore a potentially very serious issue. The CLIMB assessment includes analyses showing that in many cases adaptation actions taken now are better than adaptation actions delayed until a later time (Kirshen *et al.*, 2006).

Perspectives on adaptation by settlements

In most cases, for decision-makers in U.S. settlements considering climate change as yet one more source of possible risks and stress while they wrestle with a host of challenges every day. For them, climate change is different as an issue because it is relatively long-term in its implications, future impacts are surrounded by uncertainties, and public awareness is growing from a relatively low level to a higher level of concern. Because climate change is different in these ways, it is seldom attractive to consider allocating massive amounts of funding or management attention to current climate change actions for that reason alone. What generally makes more sense is to consider ways that actions which reduce vulnerabilities to climate change impacts (or increase prospects for realizing benefits from climate change impacts) are also desirable for other reasons as well: often referred to as "co-benefits." Examples include actions that reduce vulnerabilities to current climate variability regardless of long-term climate change, actions that add resilience to water supply and other urban infrastructures that are already stressed, and actions that make metropolitan areas more attractive for their citizens in terms of their overall quality of life.

Human settlements have used both "hard" approaches such as infrastructure and "soft" approaches such as regulations to capture services or protection from their climate and their environment. Examples include water supply and waste water systems, drainage networks, buildings, transportation systems, land use and zoning controls, water quality standards and emission caps, and tax incentives. All of these are designed in part with climate and environmental conditions in mind. The setting of regulations has always been a context of benefit-cost analysis and political realities; and infrastructure is also designed in a benefit-cost framework, subject to local design codes. The fact that both regulations and infrastructures vary considerably across the U.S. reflects cultural, economic, and environmental factors; and this suggests that mechanisms exist to respond to concerns about climate change. Urban designers and managers deal routinely with uncertainties, because they must consider uncertain demographic and other changes; thus, if climate change is properly institutionalized into the urban planning process, it can just be handled as yet another uncertainty.

Major categories of adaptation options

Adaptation strategies for human settlements, large and small, include a wide range of possibilities such as:

- Changing the location of people or activities (within or between settlements) – especially addressing the costs of sustaining built environments in vulnerable areas: e.g., siting and land use policies practices to shift from more vulnerable areas to less, adding resilience to new construction in vulnerable areas, increased awareness of changing hazards and associated risks, assistance for the less-advantaged (including actions by the private insurance sector as a likely driving force).

- Changing the spatial form of a settlement – managing growth and change over decades without excluding critical functions (e.g., architectural innovations improving the sustainability of structures, reducing transportation emissions by reducing the length of journeys to work, seeking efficiencies in resource use through integration of functions, and moving from brown spaces to green spaces). Among the alternatives receiving the most attention are encouraging "green buildings" (e.g., green roofs: Parris, 2007; see Rosenzweig *et al.*, 2006a; Rosenzweig *et al.*, 2006b) and increasing "green spaces" within urban areas (e.g., Bonsignore, 2003).

- Technological change to reduce sensitivity of physical and linkage infrastructures – e.g., more efficient and affordable interior climate control, surface materials that reduce heat island effects (Quattrochi *et al.*, 2000), waster reduction and advanced waste treatment, better warning systems and controls.

- Institutional change to improve coping capacity, including assuring effective governance, providing financial mechanisms for increasing resiliency, improving structures for coordinating among multiple jurisdictions, targeting assistance programs for especially impacted segments of the population, and adopting sustainable community development practices (Wilbanks *et al.*, 2007). Policy instruments include zoning, building and design codes, terms for financing, and early warning systems (Kirshen, Ruth, and Anderson, 2005).

- "No regrets" or low net cost policy initiatives that add resilience to the settlement and its physical capital – e.g., in coastal areas changing building codes for new construction to require coping with projected amounts of sea-level rise over the expected lifetimes of the structures.

The choice of strategies from among the options is likely to depend on "co-benefits" in terms of other social, economic, and ecological driving forces; the availability of fiscal and human resources; and political aspects of "who wins" and "who loses."

Current considerations of adaptation strategies

In most cases to date in the U.S., settlements have been more active in climate change mitigation than climate change adaptation (see box), but there are some indications that adaptation is growing as a subject of interest (Solecki and Rosenzweig, 2005; Ruth, 2006). For example, Boston has built a new wastewater treatment plant at least one-half meter higher than currently necessary to cope with sea level rise, and in a coastal flood protection plan for a site north of Boston the U.S. Corps of Engineers incorporated sea-level rise into their analysis (Easterling, Hurd, and Smith, 2004). California is considering climate change adaptation strategies as a part of its more comprehensive attention to climate change policies (Franco, 2005). And, of course, Alaska is already pursuing ways to adapt to permafrost melting and other climate change effects.

Meanwhile, in some cases settlements are taking actions for other reasons that add resilience to climate change effects. An example is the promotion of water conservation, which is reducing per capita water consumption in cities that could be subject to increased water scarcity (City of New York, 2005).

It seems very likely that local government will play an important role in climate change responses in the U.S. Many adaptation options must be evaluated at a relatively local scale in terms of their relative costs and benefits and their relationships with other urban sustainability issues, and local governments are important as guardians of public services, able to mobilize a wide range of stakeholders to contribute to broad community-based initiatives (as in the case of the London Climate Change Partnership, 2004). Because climate change impact concerns and adaptation potentials tend to cross jurisdictional boundaries in highly fragmented metropolitan areas, local actions might encourage cross-boundary interactions that would have value for other reasons as well.

While no U.S. communities have developed comprehensive programs to mitigate the effects of heat islands, some localities are recognizing the need to address these effects. In Chicago, for example, several municipal buildings have been designed to accommodate vegetated rooftops. Atlanta has had a Cool Communities “grass roots” effort to educate local and state officials and developers on strategies that can be used to mitigate the UHI. This Cool Communities effort was instrumental in getting the State of Georgia to adopt the first commercial building code in the country emphasizing the benefits of cool roofing technology (Young, 2002; Estes, Jr. *et al.*, 2003). Also see the “Excessive Heat Events Guidebook” developed by the Environmental Protection Agency in collaboration with NOAA, CDC, and DHS to provide information for municipal officials in the event of an excessive heat event: http://www.epa.gov/hiri/about/heatguidebook.html.

Alternatives for enhancing adaptation capacities

In most cases, the likelihood of effective adaptation is related to the capacity to adapt, which in turn is related to such variables as knowledge and awareness, access to fiscal and human resources, and good governance (IPCC, 2001b). Strategies for enhancing such capacities in U.S. settlements are likely to include the development and use of local expertise on climate change issues (AAG, 2003), attention to the emerging experience with climate change effects and response strategies globally and in other U.S. settlements, information sharing about adaptation potentials and constraints among settlements and their components (likely aided by modern information technology), and an emphasis on participatory decision-making, where local industries, institutions, and community groups are drawn into discussions of possible responses.

Conclusions and Recommendations

Even from a current knowledge base that is very limited, it is possible to conclude several things about effects of climate change on human settlements in the United States:

(1) Climate change will seldom be a <u>primary</u> factor in an area's development compared with other driving forces for development. It is likely to be a secondary factor, with its importance determined mainly by its interactions with other factors, except in the case of major abrupt climate change (very likely).

(2) Effects of climate change will vary considerably according to location-specific vulnerabilities, and the most vulnerable areas are likely to be Alaska, coastal and river basin locations susceptible to flooding, arid areas where water scarcity is a pressing issue, and areas whose economic bases are climate-sensitive (very likely).

(3) Except for Alaska, the main impact concerns have to do with changes in the intensity, frequency, and/or location of extreme weather events and, in some cases, water availability rather than changes in temperature (very likely).

(4) Over the time period covered by climate change projections, potentials for adaptation through technological and institutional development as well as behavioral changes are considerable, especially where such developments meet other sustainable development needs as well, especially considering the initiatives already being shown at the local level across the U.S. (extremely likely).

(5) While uncertainties are very large about specific <u>impacts</u> in specific time periods, it is possible to talk with a higher level of confidence about <u>vulnerabilities</u> to impacts for most settlements in most parts of the U.S. (virtually certain).

(6) Clarifying these vulnerabilities and reducing uncertainties about impacts would benefit from a higher level of effort in impact research (virtually certain).

(7) Promoting climate change mitigation and adaptation discussions at an urban/settlement scale will benefit from involvement of stakeholders (virtually certain).

Based on this first preliminary assessment, it is recommended that:

(1) Research on climate change effects on human settlements in the U.S., especially major metropolitan areas, be given a much higher priority in order to inform metropolitan-area scale decision-making.

(2) In particular, in-depth case studies of selected urban area impacts and responses be added without extended delay. Priorities include coastal areas of the Southeast, interior areas of the Southeast, arid areas of the Southwest, coastal areas of the Northwest, and the Great Lakes region of the Midwest.

(3) Organizations who represent urban area decision-making in the U.S. be encouraged to engage more actively in discussions of climate change impact and response issues.

ROLES OF SETTLEMENTS IN CLIMATE CHANGE MITIGATION

Although the US government has not committed itself to climate change mitigation policies at the national level, an astonishing number of state and local authorities are actively involved in considerations of how to mitigate greenhouse gas emissions (Selin and Vandeveer, 2005; Rabe, 2006; Selin, 2006). US states and cities are joining such initiatives as ICLEI (217 U.S. local government members: ICLEI, 2006), the US Mayor Climate Protection Agreement (10 mayors), the Climate Change Action Plan, the Regional Greenhouse Gas Initiative (RGGI) (Selin, 2006), and the Large Cities Climate Leadership Group (3 large cities).([1]) Those initiatives focus on emissions inventories; on such actions aimed at reducing GHG emissions as switching to more energy efficient vehicles, using more efficient furnaces and conditioning systems, and introducing renewable portfolio standards (RPS), which mandate a formal increase in the amount of electricity generated from renewable resources; on measures to adapt to negative social, economic and environmental impacts; and on actions to promote public awareness (see references in footnote 1).

Different drivers lie behind these mitigation actions. Authorities and the population at large have begun to "perceive" such possible impacts of climate change as rising sea level, extreme shifts in weather, and losses of key resources. They have realized that a reduction of GHG emissions opens opportunities for longer economic development (e.g. investment in renewable energy: Rabe, 2006). In addition, climate change can become a political priority if it is reframed in terms of local issues (i.e. air quality, energy conservation) already in the policy agenda (Betsill, 2001; Bulkeley and Betsill, 2003; Romero Lankao, 2007)

The promoters of these initiatives face challenges related partly to inertia (e.g. the time it takes to replace energy facilities and equipment with a relatively long life of 5 to 50 years: Haites *et al.*, 2007). They can also face opposition from organizations who do not favor actions to reduce GHG emissions, some of whom are prepared to bring legal challenges against state and local initiatives (Rabe, 2006:17). But the number of bottom-up grassroots activities currently under way in the US is impressive, and that number appears to be growing.

[1] ICLEI is the International Council for Local Environmental Initiatives. Local governments participating in ICLEI's Cities for Climate Protection (CCP) Campaign commit to a) conduct an energy- and emissions-inventory and forecast, b) establish an emissions target, c) develop and obtain approval for the Local Action Plan, d) Implement policies and measures, and e) monitor and verify results (ICLEI, 2006: April 20 2006 www.iclei.org). The Large Cities Climate Leadership Group is a group of cities committed to the reduction of urban carbon emissions and adapting to climate change. It was founded following the World Cities Leadership Climate Change Summit organized by the Mayor of London in October 2005. For more information on the US Mayor Climate Protection Agreement see http://www.seattle.gov/mayor/climate/

(4) Responsibility be assigned to one U.S. government agency to lead the national effort to improve information about climate change vulnerabilities, impacts, and responses for the nation's cities and smaller settlement.

(5) In all of these connections, a structure and a process be established for informing U.S. urban decision-makers about what climate change effects might mean for their cities, how to integrate climate change considerations into what they do with building codes, zoning, lending practices, etc. as mainstreamed urban decision processes.

(6) Structures be developed and supported over the long term to document experiences with urban/settlement climate change responses and provide information about these experiences to decision-making, research, and stakeholder communities.

Research Needs

According to a number of sources, including NACC, 1998; Parson *et al.*, 2003; Ruth, 2006; and Ruth, Donaghy, and Kirshen, 2004, research needs for improving the understanding of effects of climate change on human settlements in the United States include:

(1) Increasing the number of case studies of settlement vulnerabilities, impacts, and adaptive responses in a variety of different local contexts around the country.

(2) Developing better projections of climate change at the scale of U.S. metropolitan areas or smaller, including scenarios projecting extremes and scenarios involving abrupt changes.

(3) Developing realistic, socially acceptable strategies for shifting human populations and activities away from vulnerable locations.

(4) Improving the understanding of vulnerable populations within and among urban areas: populations with limited capacities for response, limited ability to affect major decisions.

(5) Improving the understanding of how urban decision-making is changing as populations become more heterogeneous and decisions become more decentralized and "democratic," especially as this affects adaptive responses.

(6) Improving abilities to associate projections of climate change in U.S. settlements with changes in other driving forces related to impacts, such as changes in metropolitan/urban patterns and technological change.

(7) Improving the understanding of relationships between settlement patterns (both regional and intra-urban) and resilience/adaptation.

(8) Considering possible impact thresholds and what they depend upon.

(9) Improving the understanding of vulnerabilities of urban inflows and outflows to climate change impacts.

(10) Improving the understanding of second and third-order impacts of climate change in urban environments, including interaction effects among different aspects of the urban system.

(11) Reviewing current regulations, guidelines, and practices related to climate change responses to help inform community decision-makers and other stakeholders about potentials for relatively small changes to make a large difference.

Meeting these needs is likely to require a rich partnership between the federal government, state and local governments, industry, non-governmental organizations, foundations, and academia, both because the federal government will have only limited resources to invest in such research and because the research effort will benefit from full participation by all.

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Synthesis and Assessment Product 4.6

Chapter 5

Effects of Global Change on Human Welfare

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5.1. Introduction

Human Welfare is an elusive concept, and there is no single, commonly accepted definition or approach to thinking about welfare. Yet there is a shared understanding that human welfare refers to aspects of individual and group life that improve life conditions and reduce injury, stress, and loss. The physical environment is one factor, among many, that may improve or reduce human welfare. Climate is one aspect of the physical environment, and can affect human welfare via economic, physical, psychological, and social pathways that influence individual perceptions of wellbeing or quality of life.

At a minimum, climate change may result in lifestyle changes and adaptive behavior with both positive and negative welfare implications. For example, warmer temperatures may change the amount of time that individuals are comfortable spending outdoors in work, recreation, or other activities, and temperature combined with other climatic changes may alter (or induce) human migration patterns. More generally, studies of climate change and the US identify an assortment of impacts on human health, on the productivity of human and natural systems, and on human settlements. Many of these impacts—ranging from changes in livelihoods to changes in water quality and supply—are likely to be linked to human welfare.

Communities are also an integral determinant of human welfare. Climate change that affects public goods—for example, damages infrastructure or causes interruptions in public services—or that disrupts patterns of production and commerce, will affect community performance in terms of overall health, poverty levels, employment, and other measures. These changes may affect individual welfare directly, in some cases due, for example, to a lost job or a more difficult commute. In other cases, individual welfare may be indirectly affected due, for example, to concern for the welfare of other individuals, or for a lack of cohesion in the community. The sustainability of a community—its ability to cope with climate change and other stressors over the long term—may be reduced by climate change that weakens the physical and social environment in a community. In the extreme, such changes may undermine the individual's sense of security or faith in government officials and government policies to accommodate change.

Despite the potential for impacts on human welfare, little (if any) research focuses directly on understanding the relationship between welfare and climate change. This is not entirely surprising, in part because no system of objective (or even subjective) metrics for measuring and tracking changes in welfare at the national level currently exists. The lack of information also reflects the difficulty of extracting (from the typical outputs of impact assessments) the information needed to link impact results qualitatively (and potentially quantitatively) to various metrics of welfare. Moreover, identifying the potentially lengthy list of climate-related changes in lifestyle, as well as in other, more tangible, features of well-being (such as income), is itself a daunting task—and likely includes changes that are not typically part of objective welfare measures, and so more elusive.

Yet, it remains that national, regional and local government decision makers, business and industry leaders, public health providers, and the general public all have an interest in knowing how climate change may affect human welfare. All of these stakeholders may experience impacts and will need to make choices and allocate resources to prepare, plan, mitigate, and recover from likely impacts of climate change-driven events. This chapter is designed to help frame and guide this process by:

- Defining human welfare and examining approaches to the study of welfare
- Creating a taxonomy of human welfare elements with concomitant climate change linkages
- Identifying human welfare measures (qualitative and quantitative)
- Describing monetary methods of assigning value to climate change's likely impacts
- Examining examples of climate change impacts on selected welfare categories and reporting monetary and other indicators of value for these categories

This chapter reports on two relevant bodies of literature: approaches to welfare that rely on qualitative assessment and quantitative measures (discussed in Section 2), and the approach adopted by the economics discipline (discussed in Section 3), which monetizes, or places money values, on quantitative effects.

Section 2, which focuses on valuation and non-monetary metrics, draws on the literature on human welfare and well-being to provide insights into a possible foundation for future research into the effects of climate change on human welfare. This section first discusses the literature defining human welfare. Next, it presents an illustrative place-based-indicators approach (the typical approach of planners and policy makers to evaluating quality of life in communities, cities, and countries). Approaches of this type represent a commonly accepted way of thinking about welfare that is linked to objective (and sometimes subjective) measures. While a place-based indicators approach has not been applied to climate change; it has the potential to provide a framework for identifying categories of human welfare that might be affected by climate change, and for making the identification of measures or metrics of welfare a more concrete enterprise in the future. To illustrate that potential, the section draws links between community welfare and climate change.

The economics discipline has been at the forefront of efforts to quantify the welfare impacts of climate change. Economists employ, however, a very specific definition of well-being—*economic* welfare—for valuing goods and services or, in this case, climate impacts. This approach is commonly used to support environmental policy decision making in many areas. Section 3 very briefly describes the basis of this approach, and the techniques that economists use (focusing on those that have been applied to estimate impacts of climate change). This section next summarizes the existing economic estimates of the *non-market* impacts of climate change.[1] An accompanying appendix provides more information on the economic approach to valuing changes in welfare, and highlights some of the challenges in applying valuation techniques to climate impacts.

The final section of the chapter summarizes some of the key points of the chapter and concludes with a brief discussion of research gaps.

[1] Because more concrete aspects of welfare, such as impacts on prices or income, may be covered by other synthesis and assessment products, this report focuses exclusively on the types of intangible amenities that directly impact quality of life, but are not traded in markets, including health, recreation, ecosystems, and climate amenities.

5.2. Human Welfare, Well-being, and Quality of Life

No single, widely accepted definition exists for the term human welfare, or for related terms such as well-being and quality of life. These terms are often used interchangeably[2] (Veenhoven, 1988, 1996, 2000; Ng, 2003; Rahman *et al.*, 2005). Academic economists, epidemiologists, health scientists, psychologists, sociologists, geographers, political scientists and urban planners have rendered their own definitions and statistical indicators of life quality at both individual and community levels.

These terms play an important role not only in academic research, but also in practical analysis and policy making. Quality of life measures may be used, for example, to measure progress in meeting quality of life goals in particular cities by planners; municipalities in New Zealand, England, Canada, and United States have constructed their own metrics of quality of life to estimate the overall well-being and opportunities available to citizens. Similarly, health-related quality of life measures can indicate progress in meeting goals; for example, the U.S. Medicare program uses metrics to track quality of life for beneficiaries and to monitor and improve health care quality (HCFR, 2004). Moreover, international agencies from the United Nations to the World Bank, and highly regarded periodicals like *The Economist*, have built composite measures of life quality to compare and rank nations of the world.

Despite these differences, welfare is typically defined and measured as a multi-dimensional concept, addressing the availability, distribution, and possession of economic assets and resources, and non-economic phenomena such as life expectancy, morbidity and mortality, literacy and educational attainment, natural resources and ecosystem services, and participatory democracy. These conceptualizations often also include social and community resources (sometimes referred to as social capital in social scientific literature), such as the presence of voluntary associations, arts, entertainment, and shared recreational amenities (see Putnam, 1993, 2000). The volume of community resources shared by a population is often called social capital.[3] These components of life quality are interrelated and correlate with subjective valuations of life satisfaction, happiness, pleasure, and the operation of successful democratic political systems (Putnam, 2000).

Life quality and human welfare are increasingly important objects of theoretical and empirical research in diverse disciplines. Two analytic approaches characterize the research literature: (1) studies that emphasize quality of life or well-being as an individual attribute or possession; and (2) studies that treat welfare as a social or economic phenomenon associated with a geographic place.

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[2] This convention of using these terms interchangeably is adopted for this chapter. As the literature on the welfare impacts of climate change develops, however, it may become important to develop a consistent interpretation of what welfare means, and to adopt a single descriptor term.

[3] The concept of social capital has been defined, in different ways, by Putnam (1993, 1995, 2000) and by Coleman (1988, 1990, 1993). For Coleman, social capital is a store of community value that is embodied in social structures and the relations between social actors, from which individuals can draw in the pursuit of private interest. Putnam's definition is similar, but places a stronger emphasis on altruism and community resources.

Individual Measures of Well-being

Approaches focusing on individuals are generally found in medical, health, cognitive, and economic sciences, and it is to these we turn briefly first, followed by place-focused indicators.

Health Focused Approaches

In medical science, quality of life is used as an outcome variable to evaluate the effectiveness of medical, therapeutic, and/or policy interventions to promote population health. Quality of life is a physiological state constituted by body structure, function, and capability that enable pursuit of stated and revealed preferences. In medical science, the concept of life quality is synonymous with good health – a life free of disease, illness, physical, and/or cognitive impairment (Raphael *et al.*, 1996, 1999, 2001).

In addition to objective measures of physical and occupational function, disease absence, or somatic sensation, life quality scientists measure an individual's perception of life satisfaction. The scientific basis of such research is that pain and/or discomfort associated with a physiological impairment are registered and experienced variably. Based on patient reports or subjective valuations, psychologists and occupational therapists have developed valid and reliable instruments to assess how mental, developmental, and physical disabilities interfere with the performance and enjoyment of life activities (Bowling, 1997; Guyatt *et al.*, 1993).

Economic and Psychological Approaches

Individual valuations of life quality also anchor economic and psychological investigations of happiness and utility. In the new science of happiness, scholars use the tools of neuroscience, experimental research, and modern statistics to estimate and discover the underlying psychological and physiological sources of happiness (for reviews see Kahneman *et al.*, 1999; Frey and Stutzer, 2002; Kahneman and Krueger, 2006). Empirical studies show, for example, that life satisfaction and happiness correlate predictably with marital status (married persons are generally happier than single people), religiosity (persons that practice religion report lower levels of stress and higher levels of life satisfaction), and individual willingness to donate time, money and effort to charitable causes. Scholars even note interesting statistical associations between features of climate (such as variations in sunlight, temperature, and extreme weather events) and self-reported levels of happiness, utility, or life satisfaction.

Individual valuations of health, psychological, and emotional well-being are sometimes summed across representative samples of a population or country to estimate correspondences between life satisfaction and "hard" indicators of living standards such as income, life expectancy, educational attainment, and environmental quality. With few exceptions,[4] cross-national analyses find that population happiness or life satisfaction increases with income levels and material standards of living (Ng, 2003) and greater personal autonomy (Diener *et al.*, 1995; Diener and Diener, 1995). In such studies, subjective valuations of life satisfaction are embedded

[4]More recent studies suggest that individual utility or happiness is not positively determined by some absolute quantity of income, wealth, or items consumed, but rather how an individual perceives his or her lot in relation to others and conditions in their past.

in broader conceptions of quality of life associated with the conditions of a geographic place, community, region or country—the social indicators approach.

The Social Indicators Approach

In this second strand of welfare research, what some refer to as the social indicators approach, scholars assemble location-specific measures of social, economic, and environmental conditions, such as employment rates, consumption flows, the availability of affordable housing, rates of crime victimization and public safety, public monies invested in education and transportation infrastructure, and local access to environmental, cultural, and recreational amenities. These place-specific variables are seen as exogenous sources of individual life quality. Scholars reason that life quality is a bundle of conditions, amenities, and lifestyle options that shape stated and revealed preferences. In technical terms, the social indicators approach treats quality of life as a latent variable, jointly determined by several causal variables that can be measured with reasonable accuracy.

The indicators approach has several advantages in the context of understanding the impacts of climate change on human welfare, which subjective individual measures do not. First, social indicators have considerable intuitive appeal, and their widespread use has not only made it familiar to both researchers and the general public, but has subjected it to considerable debate and discussion. Second, it offers considerable breadth and flexibility in terms of categories of human welfare that can be included. Third, for many of the indicators or dimensions of welfare, objective metrics exist for measurement. Last, while its strength is in providing indicators of progress on individual dimensions of quality of life, it has also been used to support aggregate or composite measures of welfare, at least for purposes of ranking or measuring progress. For example, regional scientist Richard Florida (2002a) constructed an index of technology, talent, and social tolerance measures to estimate the human capital of cities in the United States. Given the analytical strengths of the social indicators approach, it may be a good starting point for understanding the relationship between human welfare and climate change.

A Taxonomy of Quality of Life Categories

Taxonomies of place-specific quality of life typically converge on six categories or dimensions: (1) economic conditions; (2) natural resources, environment, and amenities; (3) human health; (4) public and private infrastructure; (5) government and public safety; and (6) social and cultural resources. Table 1 illustrates these categories with examples of indicators, or components of welfare for each category.[5] The table also provides illustrative metrics that have been used to represent different indicators. Finally, the last column provides some examples of climate impacts that may be linked to that category.

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[5] Sources that contributed to the development of Table 1 include: Sufian, 1993; Rahman *et al.*, 2005; and Biagi *et al.*, 2006. Insights were also derived from quality of life studies of individual cities and countries, including: http://www.bigcities.govt.nz/indicators.htm *Quality of Life in New Zealand's Large Urban Areas*; http://www.asu.edu/copp/morrison/public/qofl99.htm *What Matters in Greater Phoenix 1999 Edition: Indicators of Our Quality of Life*; and http://www.jcci.org/statistics/qualityoflife.aspx *Tracking the Quality of Life in Jacksonville*.

Table 1. Categorization of Welfare and Quality of Life

Category of Welfare	Description and Rationale	Components / Indicators of Welfare	Illustrative Metrics / Measures of Welfare	Examples of Climate Linkages
Economic conditions	The economy supports a mix of activities: opportunities for employment, a strong consumer market, funding for needed public services, and a high standard of living shared by citizens.	• Gross Domestic Product (GDP) • Economic standard of living, e.g., wealth and income, cost of living, poverty • Economic development, e.g., business and enterprise, employment • Availability of affordable housing • Distribution of income	• Income and production • Wage rates (e.g., persons at minimum wage) • Employment rates • Business startups and job creation • Housing prices • Dependence on public assistance • Families/children living in poverty • Utility costs, gasoline prices, and other prices	Reduced job opportunities and wage rates in areas dependent on natural resources, such as agricultural production in a given region that faces increased drought. Higher electricity prices resulting from increased demand for Air Conditioning as average temperatures and frequency of heat waves rise.
Natural resources, environment, and amenities	Resources enhance the quality of life of citizens; pollution and other negative environmental effects are kept below levels harmful to ecosystems, human health, and other quality of life considerations; and natural beauty and aesthetics are enhanced.	• Air, water, and land pollution • Recreational opportunities • Water supply and quality • Natural hazards and risks • Ecosystem condition and services • Biodiversity • Direct climate amenity effects	• Air and water quality indices • Regulatory compliance • Waste recycling • Acreage, visitation, funding of recreational and protected/preserved areas • Water consumption and levels • Deaths, injuries, and property loss due to natural hazards • Renewable energy generation • Endangered and threatened species	Sea Level rise could both inundate coastal wetland habitats (with negative effects on marsh and estuarine environments necessary to purify water cycle systems and support marine hatcheries) and erode recreational beaches.
Human health	Health care institutions provide medical and preventive health-care services with excellence, citizens have access to services regardless of financial means, and physical and mental health is generally high.	• Mortality risks • Morbidity and risk of illness • Quality and accessibility of health care • Health status of vulnerable populations • Prenatal and childhood health • Psychological and emotional health	• Deaths from various causes (suicide, cancer, accidents, heart disease) • Life expectancy at birth • Health insurance coverage • Hospital services and costs • Infant mortality and care of elderly • Subjective measure of health status	Increased frequency of heat waves in a larger geographical area will directly affect health, resulting in higher incidence of heat-related mortality and illness. Climate can also affect human health indirectly via effects on ecosystems and water supplies.
Public and private infrastructure	Transportation and communication infrastructure enable citizens to move around efficiently and communicate reliably.	• Affordable, and accessible public transit • Adequate road, air, and rail infrastructure • Reliable communication systems • Waste management and sewerage • Maintained and available public and private facilities • Power generation	• Mass transit use and commute times • Rail lines, and airport use and capacity • Telephones, newspapers, and internet • Waste tonnage and sewerage safety • Congestion and commute to work • Transportation accident rates • Noise pollution	Melting permafrost due to warming in the arctic damages road transport, pipeline, and utility infrastructure, which in turn leads to disrupted product and personal movements, increased repair costs, and shorter time periods for capital replacement.
Government and public safety	Governments are led by competent and responsive officials, who provide public services effectively and equitably, such as order and public safety; citizens are well-informed and participate in civic activities.	• Electoral participation • Civic engagement • Equity and opportunity • Municipal budgets and finance • Public safety • Emergency services	• Voter registration, turnout, approval • Civic organizations membership rates • Availability of public assistance programs • Debt, deficits, taxation, and spending • Crime rates and victimization • Emergency first-responders per capita	Dislocations and pressures created by climate change stressors can place significant new burdens on police, fire and emergency services.
Social and cultural resources	Social institutions provide services to those in need, support philanthropy, volunteerism, patronage of arts and leisure activities, and social interactions characterized by equality of opportunity and social harmony.	• Volunteerism • Culture, arts, entertainment, and leisure activities • Education and human capital services • Social harmony • Family and friendship networks	• Donations of time, money, and effort • Sports participation, library circulation, and support for the arts • Graduation rates and school quality • Hate, prejudice, and homelessness • Divorce rates, social supports	Disruptions in economic and political life caused by climate change stressors or extreme weather events associated with climate change could create new conflicts and place greater pressure on social differences within communities.

These categories of life quality are interrelated. For instance, as economic or social conditions in a society improve (e.g., as measured by GDP per capita and rates of adult literacy), scholars observe improvements in human health outcomes such as infant mortality, rates of morbidity, and female life expectancy at birth. Thus, while, categories and corresponding metrics of life quality are analytically separable (see Table 1), they are highly interconnected in reality.[6]

Economics as a source of welfare refers to a mix of production, consumption, and exchange activities that constitute the material well-being of a geographic place, community, region or country. Standard components of economic well-being include income, wealth, poverty, employment opportunities, and costs of living. Localities characterized by efficient and equitable allocation of economic rewards and opportunities enable material security and subjective happiness of residents (Florida, 2002a).

Natural resources, environment, and amenities as a source of welfare refers to the natural features of a place like ecosystem services and species diversity, air and water quality, natural hazards and risks, parks and recreational amenities, and resource supplies and reserves. Natural resources and amenities directly and indirectly affect economic productivity, aesthetic and spiritual values, and human health outcomes (Blomquist *et al.*, 1988; Glaeser *et al.*, 2001; Cheshire and Magrini, 2006).

Human health as a source of welfare refers to features of a geographic place, community, region or country that influence risks of mortality, morbidity, and the availability of health care services. Good health is desirable in itself as a driver of life expectancy (and the quality of life during those years), and is also critical to economic well-being by enabling labor force participation (Raphael *et al.*, 1996, 1999, 2001).

Public and private infrastructure sources of welfare refer to transportation, energy and communication technologies that enable commerce, mobility, and social connectivity. These technologies provide basic conditions for individual pursuits of well-being (Biagi *et al.*, 2006).

Government and public safety as a source of welfare refers to activities by elected representatives and bureaucratic officials that secure and maximize the public services, rights, liberties, and safety of citizens. Individuals derive happiness and utility from the employment, educational, civil rights, public service, and security efforts of their governments (Suffian, 1993).

Finally, *social and cultural resources* as a source of welfare refers to conditions of life that promote social harmony, family and friendship, and the availability of arts, entertainment, and leisure activities that enable human happiness. The terms social and creative capital have come to be associated with these factors. Communities with greater levels of social and creative capital are expected to have greater individual and community quality of life (Putnam, 2000; Florida, 2002b).

[6] More recently, scholars (Costanza et al. 2007) and government agencies (like NOAAs Coastal Service Center) have moved toward the global concept of *capital* to integrate indicators and assess community quality of life. The term capital is divided into four types: economic; physical; ecological or natural; and socio-cultural. Various metrics constitute these types of capital, and are understood as foster to community resilience and human needs of subsistence, reproduction, security, affection, understanding, participation, leisure, spirituality, creativity, identity, and freedom. See also Rothman, Amelung, and Poleme (2003).

Climate Change and Quality of Life Indicators

Social indicators are generally used to evaluate progress towards a goal—How is society doing? Who is being affected? Tracking performance for these indicators—using the types of metrics or measures indicated in Table 1—could provide information to government officials and the public on how communities and other entities are reacting to, and successfully adapting to (or failing to adapt to), climate change. The indicators and metrics included in Table 1 are not intended, however, to be either comprehensive or the best set of indicators. In any category, multiple indicators could be used; and any one of the indicators could have several measures. For example, exposure to natural hazards and risks could be measured by the percentage of a locality's tax base located in a high hazard zone, the number of people exposed to a natural hazard, the funding devoted to hazard mitigation, the costs of hazard insurance, among others. Similarly, some indicators are more amenable to objective measurement; others are more difficult to measure, such as measures of social cohesion. The point to be taken from Table 1 is that social indicators provide a diverse and potential rich perspective on human welfare.

The taxonomy presented in Table 1—or a similar taxonomy—could also be the basis for analyses of the impacts of climate change on human welfare, providing a list of important categories for research (the components or indicators of life quality), as well as appropriate metrics (e.g., employment, mortality or morbidity, etc.). The social indicators approach, and the specific taxonomy presented here, are only one of many that could be developed.[7] All taxonomies, however, face a common problem: how to aggregate metrics across individuals or individual categories of welfare and present a composite measure of welfare, against which the value of alternative adaptive or mitigating responses to climate change can be compared.

A Closer Look at Community Welfare

Looking beyond the welfare of individuals to the welfare of *communities*—networks of households, businesses, physical structures, and institutions located in geographic space—provides a broader perspective on the impacts of climate change and extreme events. The categories and metrics in Table 1 are appealing from an analytical perspective in part because they represent dimensions of welfare that are clearly important to individuals, but that also have counterparts—and can generally be measured objectively—at the community level. Thus, for example, the counterparts to individual income or health status are, at the social level, per capita income or mortality/illness rates. The concept of community welfare is linked to human communities, but is not confined to communities in urban areas, or even in industrialized cultures. Human communities in remote areas, or subsistence economies, face the same range of quality of life issues—from health to spiritual values—although they may place different weights

[7] In addition to variants on the social indicators approach, other types of taxonomies are possible—for example a taxonomy based on broad systems (atmospheric, aquatic, geologic, biological, and built environment), or on forms of capital that make up the productive base of society (natural, manufactured, human, and social). Well-being can also be viewed in terms of its endpoints: necessary material for a good life, health and bodily well-being, good social relations, security, freedom and choice, and peace of mind and spiritual existence (Rothman, Amelung, and Poleme., 2003).

on different values; the weights placed on different components of welfare are not determined a priori, but depend on community values and decision making.

Viewing social indicators and metrics through the lens of the community can be instructive in several ways. First, communities are dynamic entities, with multiple pathways of interactions among people, places, institutions, policies, structures, and enterprises. Thus, while the social indicators described in Table 1 have metrics that can be measured independently of each other, they are not determined independently within the complex reality of interdependent human systems. Second, in part because of this interdependence, the aggregate welfare of a community is more than a composite of its quality of life metrics; sustainability provides one means of approaching a concept of aggregate welfare. Third, vulnerability and adaptation are typically analyzed at the sector level: "what should agriculture, or the public health system, do to plan for or adapt to climate change." The issue can also, however, be addressed at the level of the community. Each of these issues is touched on below.

Community welfare and individual welfare

Rapid onset extreme events, such as hurricanes or tornadoes, can do serious damage to community infrastructure, public facilities and services, tax base, and overall community reputation and quality of life, from which recovery may take years and never be complete. More gradual changes in temperature and precipitation will have both negative and positive effects. For example, as discussed elsewhere in this chapter, warmer average temperatures increase risks from heat-related mortality in the summer, but decrease risks from cold-related mortality in the winter, for susceptible populations. Effects such as these will not, however, be confined to a few individual sectors, nor are the effects across all sectors independent.

To illustrate the interdependence of impacts and, thus, the analogous social indicators and metrics, consider a natural resource that is likely to be adversely affected by climate change: fish populations in estuaries, such as the Chesapeake Bay, that are already stressed by air and water pollution from industry, agriculture, and cities. In this case, while the direct effects of climate will occur to the resource itself, indirect effects can alter welfare as measured by economic, social, and human health indicators. Table 2 presents some of the possible pathways by which resource changes could affect diverse categories of quality of life; the purpose of the chart is not to assert that all these effects will occur or that they will be significant if they do occur as a result of climate change, but rather to illustrate the linkages. These linkages underscore the importance of understanding interdependencies within the community or, from another perspective, across welfare indicators. The table illustrates the general principle of complex linkages in which a general equilibrium approach can be used to model climate change impacts.

Table 2. An illustration of Possible Effects of Climate Change on Fishery Resources

Linkages/Pathways	Category of Welfare Effect	Possible Metrics
Fishery resource declines as climate changes	Natural resources, environment, and amenities	Fish populations
Recreational opportunities decline	Natural resources, environment, and amenities	Fish catch, visitation days
Related species and habitats are affected	Natural resources, environment, and amenities	Species number and diversity
Employment and wages in resource-	Economic conditions	Number of jobs, unemployment

based jobs (including recreation) fall as resources decline		rate, wages
Incomes fall as jobs are lost	Economic conditions	Per capita income
More children live in poverty as jobs are lost and incomes fall	Economic conditions	Families, children below poverty level
Access to health care that is tied to jobs and income falls	Human Health	Households without health insurance increase
Increased mortality and morbidity as a result of reduced health care	Human Health	Disease and death rates increase
Lack of jobs results in out-migration	Economic conditions	Working age population decreases
Fewer new residents attracted, because of reduced jobs and amenities (recreation)	Social and cultural resources	Population growth rate slows
Less incentive/drive to participate in community activities	Social and cultural resources	Drop in volunteerism civic participation, completion of high school

Sustainability of communities

Understanding how climate change and extreme events affect community welfare requires a different conceptual framework than that for understanding individual level impacts, such as quality of life.[8] Communities are more than the sum of their parts; they have unique aggregate identities shaped by dynamic social, economic, and environmental components. They also have life cycles, waxing and waning in response to societal and environmental changes (Diamond, 2005). Sustainability is a paramount community goal, typically expressed in terms of sustainable development in order to express the ongoing process of adaptation into the long-term future. "Climate change involves complex interactions between climatic, environment, economic, political, institutional, social, and technological processes. It cannot be addressed or comprehended in isolation from broader societal goals (such as sustainable development)…" (Banuri and Weyant, 2001). Even for a country as developed as the US, continuing growth and development creates both pressures on the natural and built environments and opportunities for moving in sustainable directions.

While the term sustainability does not have a single, widely-accepted definition, a central guideline is to *balance* economic, environmental, and social needs and values (Campbell, 1996; Berke *et al.*, 2006), sometimes portrayed as a three-legged stool. It is distinguished from quality of life by its *dynamic linking* of economic, environmental, and social components, and by its *future orientation* (Campbell, 1996; Porter, 2000). Sustainability is seen as living off of nature's interest, while protecting natural capital. Sustainability is a comprehensive social goal that transcends individual sector or impact measurements, although it can include narrower community welfare concepts such as the *healthy city* (see box). Thinking about the impacts of climate change on communities through the lens of sustainable development allows us to envision cross-sector economic, environmental, and social dynamics.

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[8] Measures of quality of life provide a database of individual welfare characteristics at various points in time, including economic conditions, natural resources and amenities, human health, public and private infrastructure, government and public safety, and social and cultural resources. Sustainable development measures are similar, but reflect more emphasis on long-term and reciprocal effects, as well as a concern for community-wide and equitable outcomes.

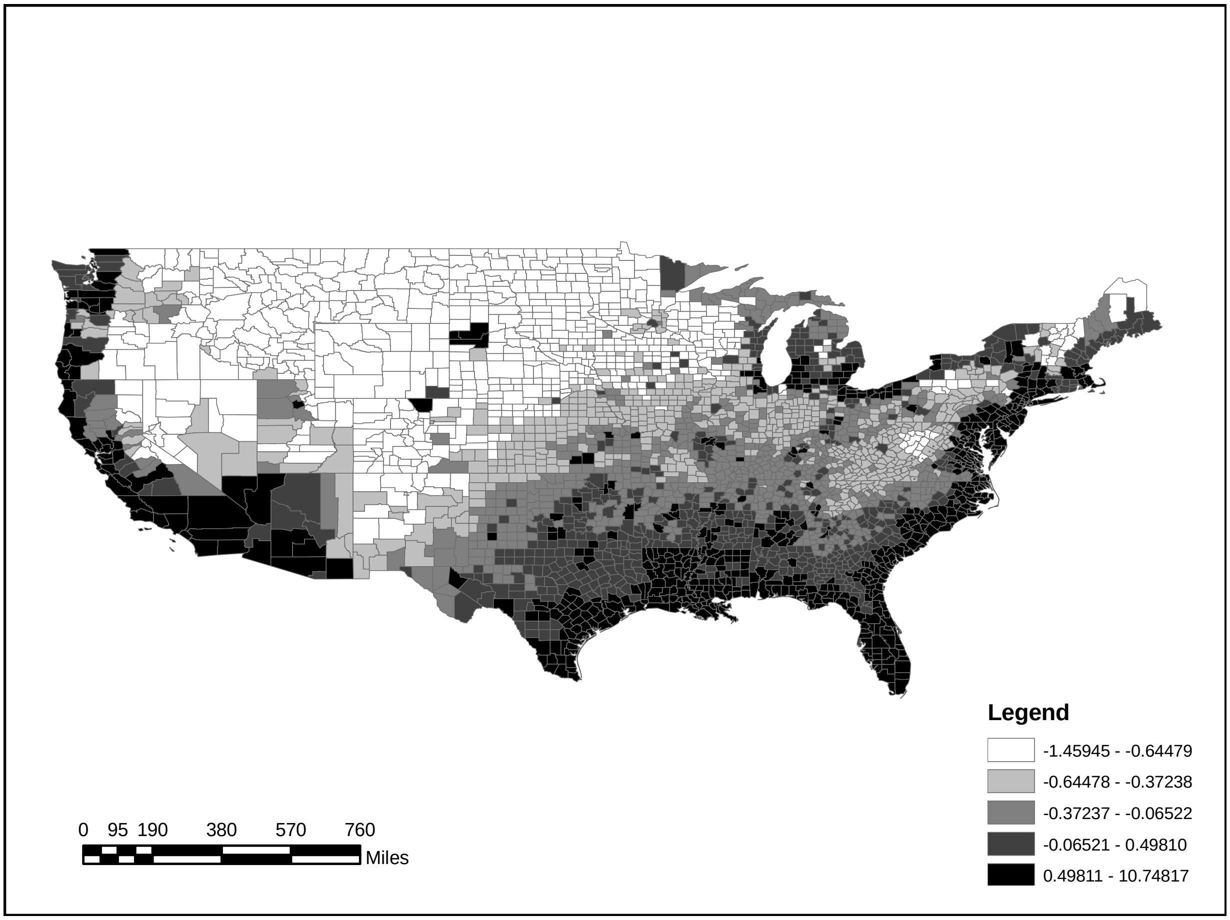
Box: Healthy City. The concept of the healthy city is derived from the concept of the sustainable city. The World Health Organization (WHO) initiated the Healthy Cities Program in 1987. WHO defines a healthy city as one that places the health and well being of its citizens at the heart of its decision-making, not one that has achieved a particular level of health but one that is conscious of health and is striving to improve it (WHO, 1997, p. 10). Health is not only a matter of morbidity and mortality, but also a matter of overall well being that encompasses sense of place, hope/despair, life satisfaction, and happiness (Northbridge *et al.*, 2003). Many U.S. communities are implementing programs to create healthy places (Morris, 2006).

Vulnerability, Adaptation, Resilience, and Communities

Responding to climate change at the community level requires understanding both vulnerability and adaptive responses that the community can take. Vulnerability of a community depends on its exposure to climate risk, how sensitive systems within that community are to climate variability and change, and the adaptive capacity of the community (i.e., how it is able to respond and protect its citizens from climate change.

While most analyses of vulnerability tend to be conducted at the regional scale, Zahran and his colleagues (forthcoming) have brought the analysis closer to the community level by mapping the geography of climate change vulnerability at the county scale. The study uses measures of both *physical vulnerability* (expected temperature change, extreme weather events, and coastal proximity) and *adaptive capacity* (as represented by economic, demographic, and civic participation variables that constitute a locality's socioeconomic capacity to commit to costly climate change policy initiatives). Their map identifies the concentrations of highly vulnerable counties as lying along the east and west coasts and Great Lakes, with medium vulnerability counties mostly inland in the southeast, southwest, and northeast. (See Figure 1, in which darker areas represent higher vulnerability).

Figure 1. Geography of Climate Change Vulnerability at the County Scale
Source: Zahran *et al.*, forthcoming.



From the perspective of the community, the goal of successful adaptation to climate impacts—particularly potentially adverse impacts—is to maintain the long-term sustainability and survival of the community. Put slightly differently, a resilient community will be one that is capable of absorbing climate changes and the shocks of extreme events without breakdowns in its economy, natural resource base, or social systems (Godschalk, 2003). Given their control over shared resources, communities have the capacity to adapt to climate change in larger and more coordinated ways than individuals, by creating plans and strategies to increase resilience in the face of future shocks, while at the same time ensuring that the negative impacts of climate change do not fall disproportionately on their most vulnerable populations (Smit and Pilifosova, 2001).

Public policies and programs are in place in the U.S. to enhance the capacity of communities to mitigate[9] damage and loss from natural hazards and extreme events (Burby, 1998; Mileti, 1999; Godschalk, forthcoming). There is a considerable body of research on responses to natural hazards, and recent research has shown that the benefits of natural hazard mitigation at the national level outweigh its costs by a factor of four to one on average (Multihazard Mitigation Council, 2005; Rose *et al.*, forthcoming). Research also has been done on the social vulnerability of communities to natural hazards (Cutter *et al.*, 2003) and the economic resilience of businesses

[9] In the natural hazards and disasters field, a single term—mitigation—refers both to adaptation to hazards and mitigation of their stresses. (See the Disaster Mitigation Act of 2000, Public Law 106-390.)

to natural hazards (Tierney, 1997; Rose, 2004). However, there is scant research on U.S. policies dealing with community adaptation to the broader impacts of climate change.

5.3. An Economic Approach to Human Welfare

Welfare, well-being, and quality of life are often viewed as multi-faceted concepts. In subjective assessments of happiness or quality of life (see the discussion in section 2), the individual makes a net evaluation of his or her current state, taking into account (at least implicitly) and balancing all the relevant facets or dimensions of that state of being. Constructing an overall statement regarding welfare from a set of objective measures, however, requires a means of weighting or ranking or otherwise aggregating these measures. The economic approach supplies one—although not the only one possible—approach to aggregation.[10]

Quantitative measures of welfare that use a common metric have two potential advantages. First, the ability to compare welfare impacts across different welfare categories makes it possible to identify and rank categories with regard to the magnitude or importance of effects. Welfare impacts can then provide a signal about the relative importance of different impacts, and so help to set priorities with regard to adaptation or research. Second, if the concept of welfare is (ideally) a net measure, then it should be possible to aggregate the effects of climate across disparate indicators. Quantitative measures that use the same metric can, potentially, be summed to generate net measures of welfare, and gauge progress over time, or under different policy or adaptation scenarios.

Given the value of welfare both as a multi-dimensional concept, and as one that facilitates comparisons, the economic approach to welfare analysis—which monetizes or puts dollar values on impacts—is one means of comparing disparate impacts. Further—and this is the second advantage of the economic approach—dollar values of impacts can be aggregated, and so provide net measures of changes in impacts that can be useful to policy makers. This section of the chapter discusses the foundation of economic valuation, the distinction between market and non-market effects (only the latter are covered in this paper), and describes some of the valuation tools that economists use for non-market effects. An appendix covers these issues in additional detail, and also describes the challenges that economic valuation faces when used as a tool for policy analysis in the long term context of climate change.

The economic approach is not appropriate in all circumstances, and is often viewed as controversial in the context of climate change. Fundamental to the approach is a notion that a key element of support for decision-making is an understanding of the magnitude of costs and benefits, so that the tradeoffs implicit in any decision can be balanced and compared. Benefit cost analysis is only one tool available to decision makers; in the context of climate change, other decision rules and tools, or other definitions of welfare, may be equally, or more releveant. Moreover, even to the extent that estimated benefits and costs provide information relevant to

[10] In part because of the difficulty in compiling the information needed for aggregation of economic measures, Jacoby (2003) proposes a portfolio approach to benefits estimation, focusing on a limited set of indicators of global climate change, of regional impact, and one global monetary measure. The set of measures would not be the only information generated and made available, but it would represent a set of variables continuously maintained and used to describe policy choices.

decision makers, some of the methodologies and data necessary to provide a relatively complete assessment may be unavailable, as discussed subsequently in this section.

Economic Valuation

The framework that economists employ reflects a specific view of human welfare and how to measure it. Economists define the value of something—be it a good, service, or state of the world—by focusing on the well-being, utility, or level of satisfaction that the individual derives. The basic economic paradigm assumes that individuals allocate their available income and time to achieve the greatest level of satisfaction. The value of a good—in terms of the utility or satisfaction it provides—is revealed by the tradeoffs that individuals make between that good and other goods, or between that good. The term "willingness to pay" (WTP) is used by economists to represent the value of something, i.e., the individual's willingness to trade money for that particular good, service, or state of the world.

Economists distinguish between market and non-market goods. Market goods are those that can be bought and sold in the market, and for which a price generally exists. Market behavior and, in particular, the prices that are paid for these goods, is a source of information on the economic value or benefit of these goods. The economic benefit—the amount that members of society would in aggregate be willing to pay for these goods—is related to, but frequently greater than, market prices.

Non-market goods are those that are not bought and sold in markets. Consequently, climate change impacts that involve non-market effects—such as health effects, loss of endangered species, and other effects—are difficult to value in monetary terms. Economists have developed techniques for measuring non-market values, by inferring economic value from behavior (including other market behavior), or by asking individuals directly.

A number of studies have attempted to value the range of effects of climate change. For the US, some of the most comprehensive studies are the series of Reports to Congress completed by U.S. EPA in 1989, Cline (1992), Nordhaus (1994), Fankhauser (1995), Mendelsohn and Neumann (1999), Nordhaus and Boyer (2000), and a body of work by Richard Tol (e.g., Tol, 2002 and Tol, 2005). In all of these studies, the focus is largely on market impacts, particularly the effects of climate change on agriculture, forestry, water resource availability, energy demand (mostly for air conditioning), coastal property, and in some cases, health.

Non-market effects, however, are less well characterized in these studies (as lamented in Smith *et al.*, 2003); where comprehensive attempts are made, they usually involve either expert judgment or very rudimentary calculations, such as multiplying the numbers of coastal wetland acres at risk of inundation from sea-level rise by an estimate of the average non-market value of a wetland. There are a number of well-done valuation analyses for non-market effects of climate change, but it is fair to characterize this literature as opportunistic in its focus - where data and methods exist, there are high quality studies, but the overall coverage of non-market effects remains inadequate.

Impacts Assessment and Monetary Valuation

The process of estimating the welfare effects of climate change involves four steps: (1) estimate climate changes; (2) estimate physical effects of climate change, (3) estimate the impacts on human and nature systems that are amenable to valuation and (4) value or monetize effects. The first step requires estimating the change in relevant measures of climate, including temperature, precipitation, sea-level rise, and the frequency and severity of extreme events. The second step involves estimating the physical effects of those changes in climate. These might include changes in ecosystem structure and function, human exposures to heat stress, changes in the geographic range of disease vectors, or flooding of coastal areas. In the third step, the physical effects of climate change are translated into measures that economists can value, for example the number and location of properties that are vulnerable to floods, or the number of individuals exposed to and sensitive to heat stress. Many analyses that reach this step in the process, but not all, also proceed on to the fourth step, valuing the changes in dollar terms. .

The simplest approach to valuation would be to apply a unit valuation approach - for example, the cost of treating a nonfatal case of heat stress or malaria attributable to climate change is a first approximation of the value of avoiding that case altogether. In many contexts, however, unit values can misrepresent the true marginal economic impact of these changes. For example, if climate change reduces the length of the ski season, individuals could engage in another recreational activity, such as golf. Whether they might prefer skiing to golf at that time and location is something economists might try to measure.

This step-by-step linear approach to effects estimation is sometimes called the "damage function" approach. A damage function approach might imply that we look at effects of climate on human health as separate and independent from effects on ecology and recreation, an assumption that ignores the complex economic interrelationships among goods and services and individual decisions regarding these. Recent research suggests that the damage function approach, under some conditions, may be both overly simplistic (Freeman, 2003) and sometimes subject to serious errors (Strzepek and Smith, 1995; Strezpek *et al.*, 1999).

Economists have a number of techniques available for moving from quantified effects to dollar values. In some cases, the values estimated in one situation—e.g., one ecosystem or species—can be transferred and used to value another. For example, value or benefits transfer is commonly used by federal agencies such as the US EPA and US Forest Service to value recreation when there is insufficient time or budget to conduct original valuation studies (Rosenberger and Loomis, 2003). Techniques commonly used by economists to value non-market goods and services include:

- *Revealed preference.* Revealed preference, sometimes referred to as the indirect valuation approach, involves inferring the value of a non-market good using data from market transactions (U.S. EPA, 2000; Freeman, 2003). For example, the value of a lake for its ability to provide a good fishing experience can be estimated by the time and money expended by the angler to fish at that particular site, relative to all other possible fishing sites. Or, the amenity value of a coastal property that is protected from storm damage (by a dune, perhaps) can be estimated by comparing the price of that property to other properties similar in every way but the enhanced storm protection.

- *Stated preference*. Stated preference methods, sometimes referred to as the direct valuation, are survey methods that estimate the value individuals place on particular non-market goods based on choices they make in hypothetical markets. The earliest stated preference studies involved simply asking individuals what they would be willing to pay for a particular non-market good. The best studies involve great care in constructing a credible, though still hypothetical, trade-off between money and the non-market good of interest (or bundle of goods) to discern individual preferences for that good and hence, WTP.
- *Replacement or avoided costs*—Replacement cost studies approach non-market values by estimating the cost to replace the services provided to individuals by the non-market good. For example, healthy coastal wetlands may provide a wide range of services to individuals who live near them (such as filtering pollutants present in water). A replacement cost approach would estimate the value of these services by estimating market costs for replacing the services provided by the wetlands. Analogously, the cost of health effects can be estimated using the cost of treating illness and of the lost workdays, etc. associated with illness.
- *Value of inputs*—This approach calculated value based on the contribution of an input into some productive process. This approach can be used to determine the value of both market and non-market inputs, for example, fertilizer, water, or soil, in farm output and profits

Value can arise even if a good or service is not explicitly consumed, or even experienced.

In the remainder of this section, we briefly discuss the relationship between climate change and four non-market effects (human health, ecosystems, recreation and tourism, and amenities), and discuss economic estimates of these effects using these techniques.

Human Health

In the US, climate change is likely to have a measurable impact on those health outcomes that have a known link with weather and climate including: heat stress and direct thermal injury, health effects related to extreme weather events, air pollution-related health effects, water- and food-borne diseases, and insect-,tick-,and rodent-borne diseases. In addition to changes in mortality and morbidity, climate change may affect health in more subtle ways. Good health is more than the absence of illness: it includes the ability to function physically (to climb stairs or walk a mile), socially (to move freely in the world), and in a work environment.

Despite our understanding of the pathways linking climate and health effects, there is some uncertainty as to the magnitude of changes in morbidity and mortality in the US, primarily due to a poor understanding of many key risk factors and confounding issues such as behavioral adaptation and variability in population vulnerability (Patz *et al.*, 2001). Economists have relatively well established (although sometimes controversial) techniques for valuing mortality and some forms of morbidity, which could, in theory be applied to quantified impacts assessments.

Overview of Health Effects of Climate Change

The US is a developed country with a temperate climate. Because of its well-developed health infrastructure, and the greater involvement of government and non-governmental agencies in disaster planning and response, the health effects from climate change are expected to be less significant than in the developing world. Nevertheless, certain regions of the US will face difficult challenges: catastrophic weather events will be more frequent and increasingly costly; the US population will age and move southward, increasing exposures to extreme heat events and vector-borne disease; injury will become a more significant cause of mortality. Outbreaks of certain vector-borne diseases will become more frequent, widespread, and will last longer, while other endemic infectious diseases will likely reduce in incidence. Specific effects on health include:

- *Heat stress and direct thermal injury*—One of the most likely effects for the US is an increase in the severity, duration, and frequency of extreme heat events (heat waves) (Kalkstein and Greene, 1997). This, coupled with an aging (and therefore more vulnerable) population, will increase the likelihood of higher mortality from exposure to excessive heat (Semenza *et al.*, 1996).
- *Injuries and other morbidity from extreme weather event*—Climate change is predicted to alter the frequency, timing, intensity, and duration of extreme weather events, such as hurricanes, floods, and tornadoes (Fowler and Hennessey, 1995). The health effects of these extreme weather events range from the direct effects such as loss of life and acute trauma to indirect effects such as loss of shelter, large-scale population displacement, damage to sanitation infrastructure (drinking water and sewage systems), interruption of food production, damage to the health care infrastructure, and psychological problems such as post traumatic stress disorder (*Curriero et al.*, 2001).
- *Air Pollution-related Health Effects*—Climate change can affect air quality by modifying local weather patterns and pollutant concentrations (such as ground level ozone), by affecting natural sources of air pollution, and by changing the distribution of airborne allergens (Morris *et al.*, 1989; Sillman and Samson, 1995). Many of these effects are localized and therefore difficult to model. Consequently, overall effects of climate change on respiratory health are variable and, therefore, difficult to predict.
- *Water- and Food-borne Diseases*—Altered weather patterns and physical effects resulting from climate change (including changes in precipitation, temperature, humidity, and water salinity) are likely to affect the distribution and prevalence of food and water borne diseases resulting from bacteria outbreaks, overloaded drinking water systems, and increases in the frequency and range of harmful algal blooms (Weniger *et al.*, 1983; MacKenzie *et al.*, 1994; Lipp and Rose, 1997; Curriero *et al.*, 2001).
- *Insect-, Tick-, and Rodent-borne Diseases*—Vector-borne diseases, such as plague, Lyme's disease, malaria, hanta virus, and dengue fever have been shown to have a distinct seasonal pattern, suggesting that they may be sensitive to climate-driven changes in rainfall and temperature (Githeko and Woodward, 2003). Because of moderating factors, such as housing quality, land-use patterns and vector control programs, it is unlikely that climate change will have a major impact on tropical diseases spreading into the US.

Valuation of Health Impacts of Climate Change

Although a large epidemiological literature exists on the health effects of climate, few studies attempts to link epidemiological findings to climate scenarios for the U.S.. These limited efforts have focused on the effects of changes in average temperature and temperature extremes on mortality, and the results have been mixed.[11]

Quantifying the relationship between climate change and cases of illness or death associated with a pathway requires a dose-response function that quantifies the relationship between a health endpoint (e.g., premature mortality due to cardiovascular disease (CVD), cases of diarrheal disease) and climate variables (e.g., temperature and humidity). The dose-response function can be used to compute the relative risk of illness or death due to a specified change in climate, e.g., an increase of 2.5°C in average July temperature. Applying this relative risk to the baseline incidence of the illness or death in a population yields an estimated number of cases associated with the climate scenario.

The epidemiological literature on average temperature changes has been reviewed by Working Group II of the IPCC (McMichael and Githeko, 2001) and more recently by McMichael *et al.* (2004) for the World Health Organization's *Global Burden of Disease*. Higher average temperatures have two effects: an increase in CVD deaths due to increases in average summer temperature and decreased CVD deaths due to a rise in average winter temperatures. Because the impact of increased heat waves on mortality is offset by the impact of reductions in extreme cold spells, the net effect of climate scenarios examined for North America (the U.S., Canada, and Cuba) is close to zero (Kunst *et al.*, 1993; Martens, 1998; McMichael *et al.*, 2004).

In contrast, the literature on the effect of temperature extremes suggests that increases in mortality due to heat waves will outweigh any reduction in mortality due to less frequent periods of extreme cold. The IPCC Second Assessment Report (1996), citing Fankhauser (1995) and Cline (1992), quotes a figure of 6,600 to 9,800 additional deaths annually in the U.S. corresponding to a doubling of CO_2 concentrations. These estimates extrapolate results from Kalkstein (1989), who examines the impact of temperature extremes on daily mortality in the summer and in the winter for 15 U.S. cities. Later studies by Kalkstein and Davis (1989) and Kalkstein and Greene (1997) analyze the effects of temperature extremes (both hot and cold) on mortality for 44 US cities in the summer and winter, and use the results of their analyses to predict the impact of future climate scenarios on mortality. Using projections from two GCMs for 2020 and 2050, Kalkstein and Greene (1997) estimate excess mortality. In 2020, under a no-control scenario, excess summer deaths in the 44 cities are estimated to increase from 1,840 to 1,981-4,100, depending on the GCM used. The corresponding figures for 2050 are 3,190-4,748 excess deaths.

Valuation of Health Effects

[11] To our knowledge, there have been no attempts to quantify the impacts of IPCC climate scenarios on cardio-vascular and respiratory morbidity in the U.S. McMichael et al. (2004) estimate the impact of climate change on DALYs (Disability-Adjusted Life Years) associated with waterborne and vector borne illness for WHO regions. These impacts are estimated to be zero for the U.S.

In benefit-cost analyses of health and safety programs, mortality risks are typically valued using the "value of a statistical life" (VSL)—the sum of what people would pay to reduce their risk of dying by small amounts that, together, add up to one statistical life. The excess deaths associated with a particular climate scenario are indeed the number of statistical lives that would be lost. In reality, climate changes will alter the *risk of death* for sensitive individuals in the population, rather than killing people with certainty. The challenge is to estimate what people would pay to avoid a small increase in their risk of dying.

Willingness to pay for a current reduction in risk of death (e.g., over the coming year) is usually estimated from compensating wage differentials in the labor market (a revealed preference method), or from contingent valuation surveys (a stated preference method) in which people are asked directly what they would pay for a reduction in their risk of dying. The basic idea behind compensating wage differentials is that jobs can be characterized by various attributes, including risk of accidental death. If workers are well-informed about risks of fatal and non-fatal injuries, and if labor markets are competitive, riskier jobs should pay more, holding worker and other job attributes constant (Viscusi, 1993). In theory, the impact of a small change in risk of death on the wage should equal the amount a worker would have to be compensated to accept this risk. For small risk changes, this is also what the worker should pay for a risk reduction.

For the compensating wage approach to yield reliable estimates of the VSL, it is necessary that workers be informed about fatal jobs risks and that there be sufficient competition in labor markets for compensating wage differentials to emerge.[12] To measure these differentials empirically requires accurate estimates of the risk of death on the job—ideally, broken down by industry and occupation. The researcher must also be able to include enough other determinants of wages that fatal job risk does not pick up the effects of other worker or job characteristics. Empirical estimates of the value of a statistical life based on compensating wage studies conducted in the U. S. lie in the range of $0.6 million to $13.5 million (1990 dollars) (Viscusi, 1993; U.S. EPA, 1997), which is the rough equivalent of $0.7 million to $16.5 million in year 2000 dollars.[13]

This challenge is compounded by the timing of climate risks: the premature mortality associated with climate change will occur in the future; indeed, the scenarios analyzed in McMichael *et al.* (2004) and in Kalkstein and Greene (1997) occur in 2020 and 2050. It is also the case that the majority of the health effects of climate change will be felt by persons 65 and over. Recent attempts to examine how the VSL varies with worker age (Viscusi and Aldy, 2006) suggest that the VSL ranges from $9.0 million (2000 dollars) for workers aged 35-44 to $3.7 million for workers aged 55-62. Contingent valuation studies (Alberini *et al.*, 2004) also suggest that the VSL may decline with age. Further, economic theory suggests that, under some assumptions, persons are willing to pay less to reduce a risk they will face in the future (say, at age 65) than they are willing to pay to reduce a risk they face today (Cropper and Sussman, 1990). Both these

[12] Estimates of compensating wage differentials are often quite sensitive to the exact specification of the wage equation. Black et al. (2003), in a reanalysis of data from U.S. compensating wage studies requested by the USEPA, conclude that the results are too unstable to be used for policy.

[13] Adjusted using the GDP implicit price deflator produced by the Bureau of Economic Analysis US Department of Commerce, available at http://www.bea.gov/national/nipaweb/TableView.asp#Mid

factors may affect the economic value that would be attached to excess mortality estimates, such as those derived by Kalkstein and Greene (1997).

The health effects associated with climate change are much broader than the changes in excess mortality discussed above. The effects of climate on illness have been examined in the literature, as indicated in the previous section; however, there have been few attempts to examine the implications of these studies for climate scenarios. In addition to quantified estimates of mortality and morbidity, themselves indications of welfare, a range of economic techniques that have been developed for use in cost-benefit analyses of health and safety regulations could be applied to many of the endpoints that may be affected by climate change, as suggested by Table 3. Before these methods could be applied; however, the impacts of climate change must be translated into physical damages.

It is also the case that good health is more than the absence of illness. All of the dimensions of functioning measured in standard questionnaires (including various health outcomes surveys (HCFR 2004)) may be affected by changes in climate. It is, however, unlikely that changes in functional limitations (stiffness of joints, difficulty walking) will be linked formally to climate or to weather. These impacts of climate are, instead, likely to be reflected in people's location decisions and, hence, reflected in wages and property values, as discussed in the subsequent section on Amenity values.

Table 3. Techniques to Value Health Effects Associated with Climate Change

Health Effect	Economic Valuation Tools
Premature mortality (associated with temperature changes, extreme weather events and air pollution effects)	Use of revealed preference techniques to value changes in risk of death (e.g., compensating wage studies). Use of stated preference studies to value changes in risk of death. Use of foregone earnings as a lower bound estimate to the value of premature mortality.
Exacerbation of cardiovascular and respiratory morbidity; morbidity associated with water-borne or vector-borne disease	Use of stated preference methods to elicit WTP to avoid illness (e.g., asthma attacks) or risk of illness (heart attack risk) or injury. Estimation of medical costs and productivity losses (known as the cost-of-illness (COI)) as a lower bound estimate of the value of avoiding illness.
Injuries associated with extreme weather events	Use of stated preference methods to elicit WTP. Use of compensating wage studies that value risk of injury. Use of COI as a lower bound estimate.
Impacts of climate change on physical functioning; sub-clinical effects	Use of stated preference methods to estimate WTP to avoid functional limitation.

Ecosystems

Human welfare depends on the Earth's ecosystems and the services that they provide, where ecosystem services may be defined as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" (Daily, 1997). These services contribute to human well-being and welfare by contributing to basic material needs, physical and psychological health, security, and economic activity, and in other ways (see Table 4). For example, a variety of ecosystem changes may be linked to changes in human health, from changes that encourage the expansion of the range of vector-borne diseases (discussed in Chapter 2) to the frequency and impact of floods and fires on human populations, due to changes in protection afforded by ecosystems.

The ability of the biosphere to continue providing these vital goods and services is being strained by human activities, such as habitat destruction, releases of pollutants, over-harvesting of plants, fish and wildlife, and the introduction of invasive species into fragile systems. The recent Millennium Ecosystem Assessment reported that of 24 vital ecosystem services, 15 were being degraded by human activity (MA, 2005). Climate change is an additional human stressor that threatens to intensify and extend these adverse impacts to biodiversity, ecosystems, and the services they provide.

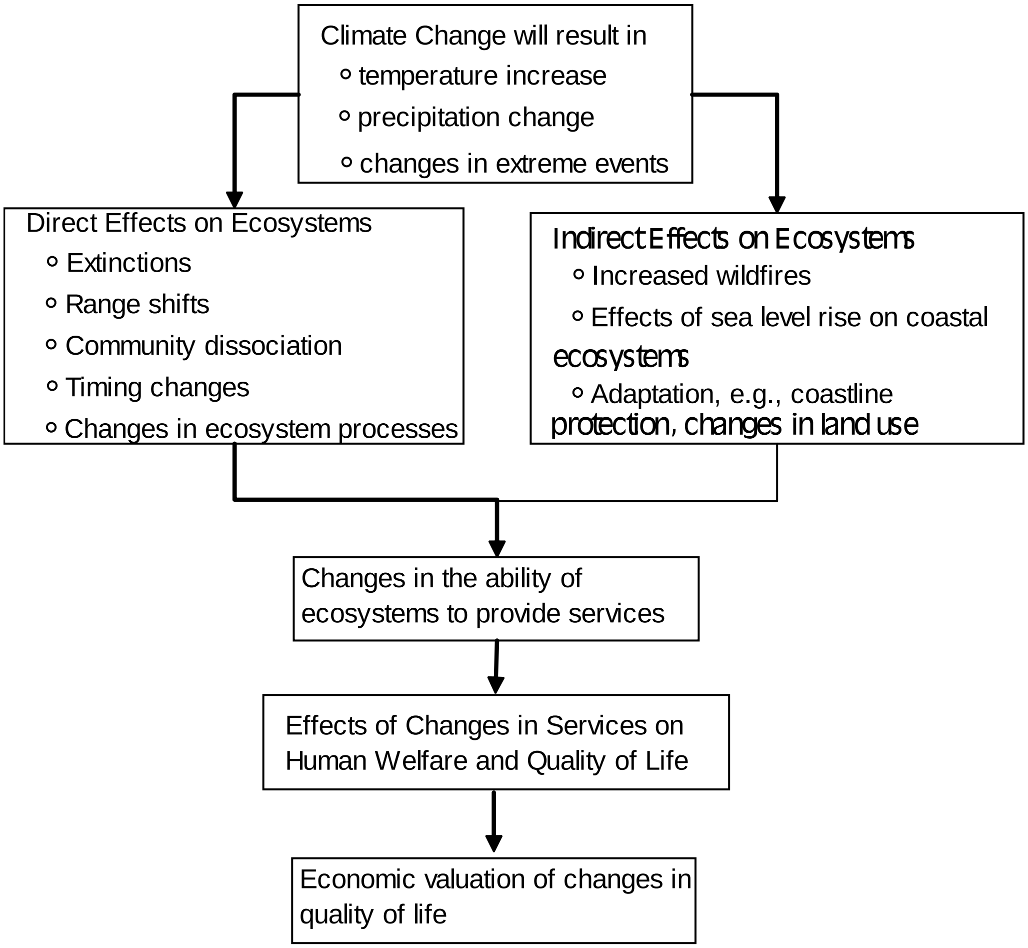
Table 4. Examples of Ecosystem Services Important to Human Welfare*

Service Category	Components of Service	Illustration of Service
Provisioning services	Food Fiber Fresh water Genetic Resources Pharmaceuticals	Harvestable fish, wildlife and plants Timber, hemp, cotton Water for drinking, hydroelectricity generation, and irrigation
Regulating services	Air quality regulation Erosion regulation Water purification Pest control Crop pollination Climate and water supply regulation Protection from natural hazards	Local and global amelioration of extremes Removal of contaminants by wetlands Removal of timber pests by birds Pollination of orchards by flying insects
Support services	Primary production Soil formation Photosynthesis Nutrient and water cycling	Conversion of solar energy to plant material Conversion of geological materials to soil by addition of organic material and bacterial activity
Cultural services	Recreation/tourism Aesthetic values Spiritual/religious values Cultural heritage	Natural sites for "green" tourism/recreation/nature viewing Existence value of rainforests and charismatic species, "holy" or "spiritual" natural sites

*Based on a classification system developed for the Millennium Ecosystem Assessment (MA, 2005)

Changes in temperature, precipitation, and other effects of climate change will have *direct* effects on ecosystems. Climate change will also *indirectly* affect ecosystems, via, for example, effects of sea level rise on coastal ecosystems, decision-makers' responses to climate change (in terms of coastline protection or land use), or increased demands on water supplies in some locations for drinking water, electricity generation, and agricultural use. Understanding how these changes alter economic welfare requires identifying and potentially valuing changes in ecosystems resulting from climate change. Getting to the point of valuation, however, requires establishing a number of linkages—from projected changes in climate to ecosystem change, to changes in services, to changes in the value of those services—as illustrated in Figure 2. The scientific community has not, thus far, focused explicitly on establishing these linkages in the context of climate change. Consequently, the published literature is somewhat fragmented, consisting of discussions of climate effects on ecosystems and of valuation of ecosystems and their services (in only a few cases do the latter focus on climate change).

Figure 2. Steps from Climate Change to Economic Valuation of Ecosystem Services



Potential Climate Change Effects On Ecosystems

Already observed effects (see reviews in Parmesan and Yohe, 2003; Root *et al.*, 2003; Parmesan and Galbraith, 2004) and modeling results indicate that climate change is likely to have major adverse impacts on ecosystems (Peters and Lovejoy, 1992; Bachelet *et al.*, 2001; Lenihan *et al.*, 2006). It is also likely that these changes will adversely affect the services that humans and human systems derive from ecosystems (MA, 2005). Climate change is likely to change ecosystems in the US within this century in the following ways.

Shifting, breakup and loss of ecological communities. As climate changes, species that are components of communities will be forced to shift their ranges to follow cooler temperatures either poleward or upward in elevation. In at least some cases, this is likely to result in the breakup of communities as organisms respond to temperature change and migrate at different rates. In general, study projections include: northern extensions of the ranges of southern broadleaf forest types, with northward contractions of the ranges of northern and boreal conifer forests; elimination of alpine tundra from much of its current range in the U.S.; and the replacement of forests by grasslands, shrub-dominated communities, and savannas, particularly in the south (e.g., VEMAP, 1995; Melillo *et al.*, 2001; Lenihan *et al.*, 2006). Because of different intrinsic rates of migration, communities may not move intact into new areas (see text box).

Effects of Climate Change on Selected US Ecosystems

At their most extreme, community changes could result in the loss of entire habitats valued by the general public. For example, sea level rise puts much of the freshwater wetland that comprises Florida Everglades National Park at risk (Glick and Clough, 2006). Even relatively modest sea level rise projections could result in the conversion of much of this low-lying area to brackish or intertidal marine and mangrove habitats. Another such extreme example is alpine tundra habitat in mountain ranges in the contiguous states. Since tundra lies at the highest elevations, there is little or no opportunity for the plants and animals that comprise this ecosystem to respond to increasing temperatures by moving upward. Thus, one of the probable effects of climate change will be the further fragmentation and loss of this unique habitat (VEMAP, 1995; Lenihan *et al.*, 2006).

California already reports an example of how climate change might modify major marine ecological communities. Over the final four decades of the 20th century the average annual ocean surface temperature off the California coast warmed by approximately 1.5^{o}C (Holbrook *et al.*, 1997). Sagarin *et al.* (1999) found that the intertidal invertebrate community at Monterey has changed since first it was characterized in the 1930s. Many of the coolwater species had retracted their ranges northward, to be replaced by southern warm water species. The community that exists there now is markedly different in its make-up from that which existed prior to warming of the coastal California Current.

Extinctions of plants and animals and reduced biodiversity. While some species may be able to adapt to changing climate conditions, others will be adversely affected. It is likely that one results of this will be that current extinction rates will be accelerated, resulting in loss in biodiversity. The most vulnerable species within the U.S. may be those that are currently confined to small, fragmented habitats that may be sensitive to climate change. This is the case with Edith's checkerspot, a western butterfly species that is already undergoing local subpopulation extinctions due to climate change (Parmesan, 1996). Other potentially vulnerable organisms include those that are restricted to alpine tundra habitats (Wang *et al.*, 2002), or to coastal habitats which may be inundated by sea level rise (Galbraith *et al.*, 2002).

Range shifts. Faced with increasing temperatures, populations of plants and animals will attempt to track their preferred climatic conditions by shifting their ranges. Range shifts will be limited by factors such as geology (in the case of plants that are confined to certain soil types), or the presence of cities, agricultural land, or other human activities that block northward migration. Some individual species in North America and the US are already undergoing range shifts (Parmesan and Galbraith, 2004). The red fox in the Canadian arctic shifted its range northward by up to 600 miles during the 20th century, with the greatest expansion occurring where temperature increases have been the largest (Hersteinsson and Macdonald, 1992). More generally, a number of bird species have shifted their ranges northward in the U.S. over the past few decades. While some of these changes may be attributable to non-climatic factors, it is likely that some are due to climate change (Parmesan and Galbraith, 2004).

Timing changes. The timing of major ecological events is often triggered or modulated by seasonal temperature change. Changes in timing may already be occurring in the breeding seasons of birds, hibernation seasons of amphibians, and emergences of butterflies in North America and Europe (Bebee, 1995; Crick *et al.*, 1997; Brown *et al.*, 1999; Dunn and Winkler, 1999; Roy and Sparks, 2000). Disconnects in timing of interdependent ecological events may be accompanied by adverse effects on sensitive organisms in the U.S. Such effects have already been observed in Europe where forest-breeding birds have been unable to advance their breeding seasons sufficiently to keep up with the earlier emergence of the arboreal caterpillars with which they feed their young. This has resulted in declining productivity and population reductions in at least one species (Both *et al.*, 2006).

Changes in ecosystem processes. Ecosystem processes, such as nutrient cycling, decomposition, carbon flow, etc., are fundamentally influenced by climate. Climate change is likely to disrupt at least some of these processes. While these effects are difficult to quantify, some types of changes can—and have been observed. Increasing temperatures over the past few decades on the North Slope of Alaska have resulted in a summer breakdown of the permanently frozen soil of the Alaskan Tundra and increased activity by soil bacteria that decompose plant material. This has accelerated the rate at which CO_2 (a breakdown product of the decomposition of the vegetation and also a greenhouse gas) is released to the atmosphere—changing the Tundra from a net sink (absorber) to a net emitter of CO_2 (Oechel *et al.*, 1993; Oechel *et al.*, 2000).

Indirect effects of climate change. Climate change may also result in "indirect" ecological effects as it triggers events (the frequency and intensity of fires, for example) that, in turn, adversely affect ecosystems. In U.S. forest habitats, increased temperatures are likely to result in increased frequency and intensity of wildfires, especially in the arid west, leading to the breakup of contiguous forests into smaller patches, separated by shrub and grass dominated communities that are more resistant to the effects of fire (Lenihan *et al.*, 2006). Other major indirect effects are likely to include the loss of coastal habitat through sea level rise (Warren and Niering, 1993; Ross *et al.*, 1994; Galbraith *et al.*, 2002), and the loss of coldwater fish communities (and the recreational fishing that they support) as water temperatures increase (Meyer *et al.*, 1999).

The linkages between these types of changes and the provision of ecosystem services is difficult to define. While ecologists have developed a number of metrics of ecosystem condition and functioning (e.g., species diversity, presence/absence of indicator species, primary productivity, nutrient cycling rates), these do not generally bear an obvious relation to metrics of services. In some cases, such as species diversity and bird population sizes, direct links might be drawn to services (in this case, opportunities for bird watching). However, in many, if not most cases, the linkages between stressor effects, change in ecosystem metrics, and service flows are more obscure. For example, it is known that freshwater wetlands can remove contaminants from surface water (Daily, 1997) and this is an important service. However, the specific ways in which wetlands do this—in terms of the ecological processes and linkages within the system—are not well understood, are likely to vary between different types of wetland (e.g., beaver swamps vs. cattail stands), and may vary spatially and temporally.

Economic Valuation of Effects on Ecosystems

Ecosystems are generally considered non-market goods: although land itself can be bought and sold, there is no market for ecosystem services per se, and so land value is only a partial measure of the value of the full range of ecosystem services provided. From the perspective of human welfare and climate change, however, we are concerned less with the ecosystems or the land on which they are located, than with the diverse services they provide, as illustrated in Table 4.

Economic valuation of changes in ecosystem services will be easier in cases where there are relationships between market goods and the ecosystem services being valued. For example, ecosystem changes may result in changes in the availability of goods and services that are traded on markets, as in the case of provisioning services, such as food, fisheries, pharmaceuticals etc. In other cases, market counterparts to the services may exist, as in the case of regulating services; for example, insights into the value of water purification services can come from looking at the (avoided) cost of a water purification plant to substitute for the ecosystem service. Services, such as water purification, may also have relationships with market goods and services (e.g., as an input into the production process) that make it possible to estimate economic values at least in part or approximately.

Many ecosystem services are, however, truly non-market, in that there are no market counterparts by which to estimate their value. Recreational uses of ecosystems fall into this category, and so economists have developed means of inferring values from behavior (e.g., travel cost), as discussed in the next section), and in other ways. Most of the support services and cultural values of ecosystems are also in the “true” non-market category. It can be difficult to define, much less to measure the value of changes in these non-market services. To do so, economists typically use stated preference (direct valuation) methods for these services, a method that can be used not only for non-market services, but also to value services in other categories, such as the value that individuals place on clean drinking water or swimming facilities.

Below we report on the relevant literature in two categories. First, we report on studies that have looked at the non-market value of specific ecosystems or species. Since only a few of these studies attempt to value the impacts of climate change on ecosystems, we also highlight some non-market studies from the more general literature on ecosystem valuation, which can provide insights into the magnitude of potential values of services that might be vulnerable to climate change. Next we look at a different approach to valuation of ecosystems—a more “top-down” approach—which has been adopted both to look at the effects of climate change and more broadly at the total value of ecosystems.

Valuation of the Effects of Climate Change on Selected Ecosystem and Species

Although climate change appears in a number of studies, it is often as a context for the scenario presented in the study for valuation, and so the study cannot be interpreted as valuation of climate change or climate effects per se. Only a few studies can be said to value the economic impacts of climate change on a particular ecosystem.

Two studies, Layton and and Brown (2000) and Layton and Levine (2002) estimate total values for preventing Colorado (Rocky Mountain) forest loss due to climate change, based on data from the same revealed preference survey. The survey was conducted with Denver-area residents, who were likely to be familiar with forested regions in their nearby mountains. Respondents were given detailed information about likely climate change impacts on these forests, including likely changes in tree line elevation over both 60-year and ,150 year time horizon. Layton and Brown (2000) found values of $10 to $100 per month, per respondent, to prevent forest loss, with the range depending, in part, on the amount of forest lost. Layton and Levine (2002) reanalyzed the same data set, using a different approach that focuses on understanding respondents' least preferred, as well as most preferred, choices. They found that respondents' value of forest protection depends also on the time horizon—preventing effects that occur further into the future are valued less than nearer term effects.

Kinnell *et al.* (2002) design and implement several versions of stated preference studies that explore the impact of wild bird (duck) loss due to either adverse agricultural practices, climate change, or both. The respondents consist of Pennsylvania duck hunters, although the hypothetical ecosystem impacts occur in the Prairie Pothole region, which is in the northern Midwestern states and parts of Canada. The authors consider a hypothetical loss in duck populations, with a scenario that presents some respondents with a 30 percent loss, and other with a 74 percent loss, some with a 40 year time horizon, and others with a 100 year time horizon. The study cannot be viewed as an estimate of willingness to pay to avoid climate change; however, it is interesting because it suggests that recreational enthusiasts are willing to pay for ecosystem impacts that they do not necessarily expect to use. In addition, the study provides evidence that the context of climate change or other cause of ecosystem harm (in this case agricultural practices)—irrespective of the level of harm—may affect respondents' valuation of the harm.

Very few studies have valued climate change impacts on ecosystems. However, economists have conducted numerous studies (primarily using direct valuation methods) of ecosystem values in particular geographic locations, often focusing on specific charismatic species, or specific types of ecosystems, such as wetlands, in the location. In some cases, the estimated values are linked to specific services that the species or ecosystem provides, but in many the services provided are somewhat ambiguous, and it is not always clear what aspect of the species, habitat, or ecosystem is driving the individual respondent's economic valuation.

A number of studies indicate that people value the protection of species or ecosystems. Some of these studies find potentially significant species values, ranging from a few dollars to hundreds of dollars per year, per person. For example, MacMillan *et al.* (2001) estimate the value of restoring woodlands habitat, and separately evaluate the reintroduction of the wolf and the beaver to Scottish highlands. In the United States, species such as salmon and spotted owls, as well as their habitat, have been examined in connection to their respective controversies.

Studies have also looked at the value of ecosystems or changes in ecosystems. In the former case, economists use either the value of productive output (harvest) as an indicator of value, or respondents value protecting the ecosystem. For example, numerous coastal wetland and beach protection studies have used a variety of non-market valuation approaches. A survey of a number of these studies reports values ranging from $198 to approximately $1500 per acre (Woodward and Wui, 2001).

Some studies have looked explicitly at the services provided by ecosystems. For example, Loomis *et al.* (2000) considers restoration of several ecosystem services (dilution of wastewater, purification, erosion control, as fish and wildlife habitat, and recreation) for a 45-mile section of the Platte River, which runs east from the State of Colorado into western Nebraska. Average values are about $21 per month for these additional ecosystem services for the in-person interviewees. While these studies and their values are generally informative, transferring values from studies like the ones above to other ecosystems, and using the results to estimate values associated with climate change impacts, can be problematic.

Top-down Approaches to Valuing the Effects of Climate Change and Ecosystem Services

From the perspective of deriving values for ecosystem changes (or changes in ecosystem services) associated with climatic changes, one difficulty with the above studies is that the focus is on discrete changes to particular species or geographic areas. It is therefore difficult to know how these studies relate to, or shed light on, the types of widespread and far-reaching changes to ecosystems (and the services they provide) that will result from climate change. Consequently, some studies have attempted to value ecosystems in a more aggregate or holistic manner. While these studies do not focus specifically on the US, they are indicative of an alternative approach that recognizes the interdependence of ecosystems, and therefore deserve some discussion.

Several models include values for non-market damages, worldwide, resulting from projected climate change. These impact studies have been conducted at a highly aggregated level; most of the models are calibrated using studies of the U.S. which are then scaled for application to other regions (Warren *et al.*, 2006).

A study of total ecosystems value, but not undertaken in the context of climate change, is the highly publicized study by Costanza *et al.* (1997), which offers a controversial look at valuing the "entire biosphere." Because their reported estimated average value of $33 trillion per year exceeds the global gross national product, economists have a difficult time reconciling this estimate with the concept of economic value (WTP); since WTP cannot equal twice income. Ehrlich and Ehrlich (1996) and Pimental *et al.* (1997) are studies by natural scientists that have attempted to value ecosystems or in the case of the latter, biodiversity. These are important attempts to indicate the value of ecosystems, but the accuracy and reliability of the values are questionable. To paraphrase a study by several prominent environmental economists that is slightly critical of all of these studies, economists do not have any fundamental difference of opinion with these natural scientists about the importance of ecosystems and biodiversity, rather it is with the correct use of economic value concepts in these applications (see Bockstael *et al.*, 2000).

Recreational Activities and Opportunities

Ecosystems provide humans with a range of services, including outdoor recreational opportunities. In turn, outdoor recreation contributes to individual wellbeing by providing physical and psychological health benefits. In addition, tourism is one of the largest economic sectors in the world, and it is also one of the fastest growing (Hamilton and Toll, 2004); the jobs created by recreational tourism provide economic benefits not only to individuals but also to the community.[14] A number of studies have looked at the likely qualitative effects of climate change on recreational opportunities (i.e., resources available) and activities in the US, but only a few have taken this literature the additional step of estimating the implications of climate change for

[14] Effects on jobs, income, and similar metrics are considered market impacts, and are not discussed here.

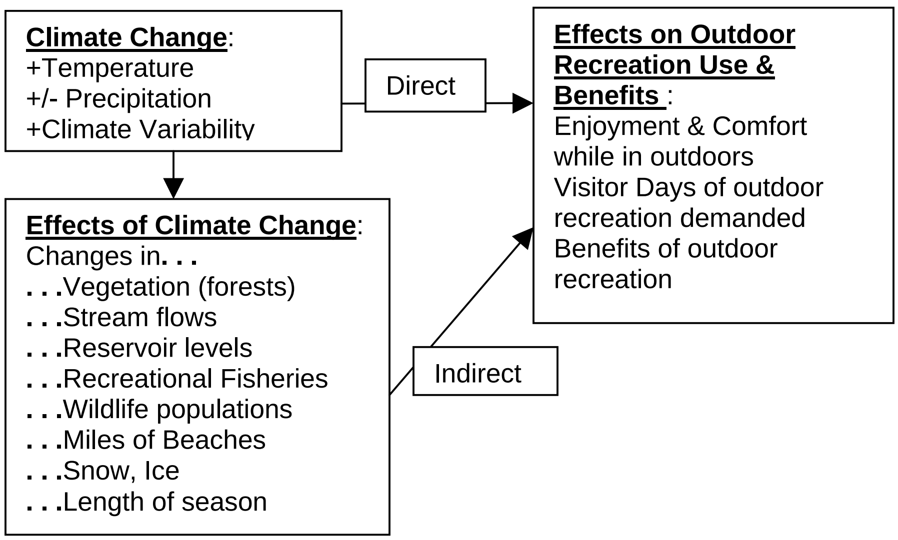
visitation days or economic welfare. This section describes the results of this research into the impacts on several forms of recreation and summarizes the economic benefits and losses associated with these changes at the national level.

Direct and Indirect Effects of Climate Change on Recreation

Slightly more than 90% of the U.S. population participates in some form of outdoor recreation, representing nearly 270 million participants (Cordell *et al*., 1999), and several billion days spent each year in a wide variety of outdoor recreation activities. According to Cordell *et al.* (1999), the number of *people* participating in outdoor recreation is highest for walking (67%), visiting a beach or lakeshore or river (62%), sightseeing (56%), swimming (54%) and picnicking (49%). Most *days* are spent in activities such as walking, biking, sightseeing, bird-watching, and wildlife viewing (Cordell *et al.*, 1999), because of the high number of days per bicycle rider and bird watchers, but the range of outdoor recreation activities in the United States is as diverse as its people and environment. While camping, hunting, backpacking and horseback riding attract a fraction of the people who go biking or bird-watching, these other specialized activities provide a very high value to its devotees. Many of these devotees of specialized outdoor recreation activities are people who “work to live,” i.e., specialized weekend recreation is one of their rewards for the 40+ hour workweek.

Climate change resulting from increasing average temperatures as well as changes in precipitation, weather variability (including more extreme weather events), and sea level rise, has the potential to affect recreation and tourism along two pathways. Figure 3 illustrates these direct and indirect effects of climate change on recreation. Since much recreation and tourism occurs out of doors, increased temperature and precipitation have a direct effect on the enjoyment of these activities, and on the desired number of visitor days and associated level of visitor spending (as well as tourism employment). In addition, much outdoor recreation and tourism depends on the availability and quality of natural resources (Wall, 1998), Consequently, climate change can also indirectly affect the outdoor recreational experience by affecting the quality and availability of natural resources (and, thus, the availability and quality of recreational experience) used for recreation such as beaches, forests, wetlands, snow, and wildlife.

Figure 3. Direct and Indirect Effects of Climate Change on Recreation



Effects of climate change can be both positive and negative. The length of season for and desirability of several of the most popular activities—walking, visiting a beach or lakeshore or river, sightseeing, swimming, and picnicking (Cordell *et al.*, 1999)—will likely be enhanced by small near term increases in temperature. However, long-term higher increases in temperature may eventually have adverse effects on activities like walking, and result in sufficient sea level rise to reduce publicly accessible beach areas, just at the time when demand for beach recreation to escape the heat is increasing. In contrast, some activities are likely to be unambiguously harmed by even small increase in global warming, such as snow and ice activities.

In some ways, one can interpret the direct effects of climate change as influencing the demand for recreation and the indirect effects as influencing the supply of recreation opportunities. For example, warmer temperatures make whitewater boating more desirable. However, the warmer temperatures may reduce river flows since there is less snowpack, higher evapotranspiration, and greater water diversions for irrigated agriculture. Some studies cited below look only at the direct effects, while others represent the combined effect of the direct and indirect pathways.

Direct Effects of Climate Change on Outdoor Recreation

To date, most studies of the direct effects of climate change on recreation and tourism have been qualitative, although a few have been quantitative. Qualitatively, we would expect both positive and negative effects of climate change on different recreational activities. Many of the qualitative studies rely simply on intuition to suggest that increases in air and water temperatures will have a positive effect on outdoor recreation visitation in two ways: (a) more enjoyment from the activity; (b) a longer season in which to enjoy the activity (DeFreitas, 2005; Scott and Jones, 2005). Hall and Highman (2005) note that climate change may provide more days of "ideal" temperatures for water based recreation activities and some land based recreation activities such as camping, picnicking and golf.

The most obvious harmed recreation activities from warmer climate are snow sports such as downhill and cross country skiing, snowmobiling, ice fishing, and snowshoeing. Reductions in visitor use (see, for example, the studies reported in Table 5) occur primarily from shorter season, particularly early in the year at such traditional times as Thanksgiving and late in the year such as Spring break. But with warmer temperatures, there is also less precipitation as snow and more as rain on snow, which contributes to a much thinner snowpack and harder snow. Further, recreating in freezing rain or slushy temperatures is not a pleasant experience, reducing benefits from skiing, snowshoeing, and snowmobiling, further reducing use.

Some recreation areas that are already quite warm during the summer recreation season will see decreases in use. For example, the Death Valley National Park, Joshua Tree National Park, and Mesa Verde National Park are all predicted to be "intolerably hot" reducing visitation (Saunders and Easley, 2006).

Most quantitative studies of the effects of climate change on recreation evaluate specific projected changes in temperature and/or precipitation, such as a 2.5°C increase in temperature over the next fifty years. Two recent quantitative studies look at effects of temperature change in Canadian recreation.[15] Scott and Jones (2005) predict that the golf season in Banff, Canada could be extended by at least one week and up to eight weeks, increasing rounds of golf played between +50% and 86%. (Similar increases might be expected for golf in northern tier states of the U.S. such as Minnesota, Wisconsin, New York, etc. with longer golf seasons.) Scott, et al. (2006) and Scott and Jones (2005) suggest that some of the previously predicted large (-30% to -50%) reductions in length of ski seasons at northern ski areas (e.g., in Canada, Michigan, and Vermont) can be reduced (to –5% to –25%) through the use of advanced snowmaking. While use of advanced snowmaking to minimize reductions in ski season seems plausible for the studied northern ski areas, it is unlikely to benefit ski areas in California, New Mexico, Oregon and West Virginia where the Thanksgiving and Spring Break periods are already too warm for successful snowmaking or retention of snow made.

Some studies have used natural variations in temperature to evaluate the effects of climate on recreation (including measures on monthly, seasonal and inter-annual variation). Two of these have found that while visitation increases with initial increases in temperature, visitation actually decreases as temperature increases even further (Hamilton and Tol, 2004; Loomis and Richardson, 2006). Two of the quantitative studies, which look not only at visitor days but also at monetary measures of economic welfare, are discussed in more detail below, following the discussion of indirect effects, and the results for quantitative changes in visitor days are presented in Table 5.

Indirect Effects of Climate Change on Outdoor Recreation

While increased temperature may increase the demand for some outdoor recreation activities, in some cases climate change may reduce the supply of natural resources on which those

[15] Scott and Jones (2005) used +1C to +5C in their scenarios and Scott et al. (2006) used +1.5C to +3C in their low impact scenario and +2C to +8C in their high impact scenario.

recreational activities depend. As noted above, reduced snowpack for winter activities has been projected in the Great Lakes (Scott *et al.*, 2005), in northern Arizona (Bark-Hodgins and Colby, 2006) and at a representative set of ski areas in the U.S. (Loomis and Crespi, 1999).[16]

For example, lower in-stream flows and lower reservoir levels have consistently been shown to reduce recreation use and benefits (Shaw, 2005). Thus, changes associated with climate can reduce opportunities for summer boating and other water sports. When less precipitation falls as snow in the Winter, and more falls as rain in the Spring, early Spring season run-off will increase. Summer river flows will be correspondingly lower, at time when demand for whitewater boating is higher. Human responses to the physical changes associated with climate change may exacerbate natural effects reducing recreational opportunities. For example, many current reservoirs are not designed to handle huge spring inflows, and thus this water may be "spilled," which lowers reservoir levels during the summer season. These lower reservoir levels are then drawn down more rapidly as higher temperatures increase evapotranspiration and increase irrigation releases. In turn, the resulting lower reservoir may leave boat docks, marinas, and boat ramps inaccessible.

Ecosystems that provide recreational benefits may also be at risk from climate change. Wetlands are another recreational environment that is at risk from climate change. Wetland based recreation include wildlife viewing and waterfowl hunting. With sea level rise, many existing coastal wetlands will be lost, and given existing development inland, these lost wetlands are not likely be naturally replaced (Wall, 1998). The higher temperatures and reduced water availability is also expected to adversely affect freshwater wetlands in the interior of the country. As such waterfowl hunting and wildlife viewing may be adversely affected.

Higher water temperatures and lower stream flows are predicted to reduce coldwater trout fisheries (U.S. E.P.A., 1995; Ahn, et al. 2000) and as well as native and hatchery stocks of Chinook salmon in the Pacific Northwest (Anderson, et al. 1993). Given trout and Chinook salmon's sensitivity to warm water temperatures these affects are not surprising. However, Anderson et al's estimated magnitude of 50% to 100% reduction in Chinook spawning returns is quite large. Reductions of such magnitude will have a substantial adverse effect on recreational salmon catch rates, and possibly whether recreational fishing would even be allowed to continue in some areas of the Pacific Northwest. However, from a national viewpoint, fishing participation for trout, cool water species and warm water species dominates geographically specialized fishing like Chinook salmon. Warmer water temperatures are predicted to eliminate stream trout fishing in 8-10 states and result in a 50% reduction in coldwater stream habitat in another 11-16 states depending on the GCM model used (U.S. E.P.A., 1995). This could adversely effect up to 25% of U.S. fishing days (Vaughan and Russell, 1982). This 25% loss is likely to be an upper limit as some coldwater stream anglers may substitute to less affected coldwater lakes/reservoirs or switch to cool/warmwater species such as bass (U.S. E.P.A., 1995). Studies that do better account for substitution effects, such as Ahn et al. (2000) indicate a 2-20%

[16] Higher temperatures (while they increase snowmelt reducing the snow skiing season) may have two subtle effects: (a) stimulating demand for snow skiing due to warmer temperatures, for those skiers who prefer "spring skiing" due to the warmer temperatures even if the snow conditions are less than ide; and (b) reduced snowmelt opens up the high mountains for hiking, backpacking and mountain biking activities somewhat earlier than is the case now, which may lead to increases in those visitor use days.

drop in benefits of trout fishing depending on the the predicted degree of temperature increase which ranged from +1C to +5C.

Sea level rise reducing beach area and beach erosion are concerns with climate change that may make it difficult to accommodate the increased demand for beach recreation (Yohe *et al.*, 1999). Forests for recreation may also be adversely affected by climate change. Although forests may slowly migrate northward and into higher elevations, in the short run there may be dieback of forests at the current forest edges (as these areas become too hot), resulting in a loss of forests for recreation.

Saunders and Easley (2006) find that most National Park resources will be adversely affected by climate change. The most common adverse effects are reductions in some wildlife species, loss of coldwater fishing opportunities and increasing park closures due to wildfire associated with stressed and dying forest stands. The text box discusses in more detail potential effects of climate change on one park: Rocky Mountain National Park, which has been the subject of both ecological and economic analysis.

Economic Studies of Effects of Climate on Recreation

Changes in economic welfare due to the effects of climate change on non-market resources, such as recreation, can be evaluated in several ways. First, since decisions regarding recreational activities depend on both direct and indirect effects of climate, changes in human well-being (as a result of these changes) will be reflected in changes in visitor use. Social scientists believe changes in visitor use are motivated by people "voting with their feet" to maintain or improve their well being. In the face of higher temperatures, people may seek relief, for example, by frequenting the beach or water skiing at reservoirs more often to cool down. Similarly, reduced opportunities for recreation due to indirect effects of climate change will also be reflected in reduced visitation days. Thus one metric of effects on human welfare are changes in visitation days.

Second, recreational trips—for example, to reservoirs and beaches—have economic implications to the visitor and the economy. Visitors allocate more of their scarce time and household budgets to the recreational activities that are now more preferred in a warmer climate. This reflects their "willingness to pay" for these recreational activities, which is a monetary measure of the benefits they receive from the activity. Numerous economic studies provide estimates of the value of changes in diverse recreational activities, using various economic techniques (such as travel cost[17] analysis and stated preference methods) (see Section 3 of this chapter and the chapter Appendix for more information). While these studies typically do not focus directly on climate change, they can be used to extract values for the types of changes that are projected to be associated with climate change.

Third, some people who do not currently visit unique natural environments may value climate stabilization policies that preserve these natural environments for future visitation. These people

[17] The travel cost method traces out a demand curve for recreation using travel cost as proxies for the price of recreation, along with the corresponding number of trips individual visitors take at these travel costs. From the demand curve, the net willingness to pay or consumer surplus is calculated.

have what economists call a value for preserving their option—their ability— to visit the environments in the future (Bishop, 1982). This option value is much like purchasing trip insurance to guarantee that if one wanted to go in the future, that conditions would be as they are today.

Changes in visitation days

Two studies (Loomis and Crespi, 1999; Mendelsohn and Markowski 1999) have examined the effects of climate on recreational opportunities comprehensively for the entire US. These studies both examined the effects of a +2.5C increase in temperature along with a +7% increase in precipitation. The studies used similar methodologies to estimate visitor days for a range of recreational opportunities. Each study looked at slightly different effects, but between them examined a mix of direct and indirect climate effects, including direct effects of higher temperatures on golf and beach recreation visitor days, and indirect effects of snow cover on skiing. Both studies estimate changes in visitation days due to climate change, and then use the results of a number of economic valuation studies to place monetary values on the visitation days. The studies find that, as expected, near term global warming will increase participation in activities such as water based recreation, and reduce participation in snow sports.

Table 5 presents the results of the two studies. The results suggest that relatively high participation recreation activities such as beach and stream recreation gain, and low participation activities like snow skiing lose. Although the percentage drop in visitor days of snow sports is much larger than the percentage increase in visitor days in water based recreation, the larger number of water based participants more than offsets the loss in the low participation snow sports. Thus, on net, there is an overall net gain in visitation associated with the assumed increases of +2.5°C in temperature and +7% in precipitation.[18]

Table 5. Comparison of Changes in United States Visitor Days With Climate Change

Activity	Loomis and Crespi (1999)	Mendelsohn and Markowski (1999)
Boating	9.2%	36.1%
Camping	-2.0%	-12.7%
Fishing	3.5%	39.0%
Golf	13.6%	4.0%
Hunting	-1.2%	no change
Snow Skiing	-52.0%	-39.0%
Wildlife Viewing	-0.1%	-38.4%
Beach Recreation	14.1%	not estimated
Stream Recreation	3.4%	included in boating
Gain in Visitor Benefits (in Billions)	$2.74	$2.80

[18] Geographic regions within the U.S. will experience different gains and losses. Currently hot areas with less access to water resources (e.g., New Mexico) may suffer net overall reductions in recreation use to due higher heat that makes walking, sightseeing, and picnicking less desirable. States with substantial water resources (lakes, seashores) may gain visitor days and tourism. Currently cold areas such as the Dakotas and New York may see increases in some recreation due to longer summer seasons.

The methods used to forecast visitation were slightly different between the two studies. To estimate visitor days for all recreation activities, Mendelsohn and Markowski regressed state level data on visitation by recreation activity as a function of land area, water area, population, monthly temperature and monthly precipitation. The Loomis and Crespi study used a similar approach to Mendelsohhn and Markowski for some activities, such as golf. Other forecasting techniques were used for other activities; for example, for beach recreation, they used detailed data on to individual beaches in the Northeastern, Southern and Western U.S. to estimate three regional regression equations to predict beach use, and the response of reservoir recreation to climate change was analyzed using visitation at U.S. Army Corps of Engineers reservoirs.

The Loomis and Crespi study included indirect, as well as direct, effects, for some of the recreational activities. For example, the reservoir models incorporated climate induced reductions in reservoir surface area besides temperature and precipitation. Similarly, the estimate of visitor days for snowskiing used predicted changes in the number of days of minimum snow cover to adjust skier days proportionally. In some cases, only indirect (supply) effects were included, as in the case of stream recreation, water fowl hunting, bird viewing and forest recreation. Since these estimates do not include changes in visitation associated with direct effects of climate we have less confidence in the accuracy of these results, than we do for reservoir recreation which takes into account both demand and supply effects on recreation use.

Valuation of gains and losses in visitor days

Since different activities may have different levels of enjoyment provided to the visitor (and, therefore, different economic values), adding up changes in visitation days to produce a "net change" is not an accurate representation of the overall change in well-being. The two studies discussed above used net willingness to pay as a measure of value of each day of recreation (Section 3 of this chapter provides a discussion of the concept of willingness to pay as a common economic measure of changes in welfare).

To date there have been few original or primary valuation studies of climate change per se on recreation; the case study on Rocky Mountain National Park provides one of the few examples—but see also a study by Scott and Jones (2005) on Banff National Park, Scott *et al.* (2006) for a reassessment of snow skiing, and Pendleton and Mendelsohn (1998) on fishing. There have, however, been hundreds of recreation valuation studies; the values from these studies (generally travel cost or stated preference) can be applied to other applications using a "benefit transfer" approach, and applying average values of recreation from previous studies to value their respective visitor days.

The overall net gain in visitor benefits are estimated by both the Loomis and Crespi (1999) disaggregated activity approach and the state level approach of Mendelsohn and Markowski (1999) at about $2.8 billion. Upwards of +5°C still increases benefits according to both of these studies. However, as noted below in our case study of Rocky Mountain National Park, extreme heat is likely to cause these visitor benefits to decrease at some point.

Visitors are of course somewhat adaptable to climate change in the recreation activities they choose and when they choose them. Thus, recreation represents one situation with opportunities to reduce the adverse impacts of climate change, or increase its benefits, via adaptation. As noted by Hamilton and Tol (2004) warmer temperatures may shift visitors northward, and up into the mountains. Thus currently cool areas (e.g. Maine, Minnesota, Washington) may gain and warm areas (e.g., Florida, Arizona) may get less tourism.

Some adaptive responses can be expensive, and may be of limited effectiveness; such as snowmaking at night, which is often mentioned as a adaptation for downhill skiing (Irland *et al.*, 2001). Other adaptive behavior may include moving some outdoor recreation activities indoors. For example, bouldering is now taking place in climbing gyms on artificial climbing walls. Running on a treadmill in an air conditioned gym may be a substitute for running out of doors for some people, but casual observation suggests that many people prefer to run out doors when weather permits. Unless preferences adjust to increased temperatures, there may be a loss in human well being from substituting the treadmill in the air conditioned gym for the out of doors.

Case Study of the Effects of Climate Change on Alpine National Park

One of the National Parks most closely studied to determine the net effect of direct and indirect effect of climate change on visitation, visitor benefits and tourism employment is Rocky Mountain National Park (RMNP) in Colorado. This alpine national park, is located at elevations ranging from 7,000 feet to 14,000 feet above sea level. It is known for elk viewing, hiking, tundra flowers, snowcapped peaks, and one of Colorado's most visible and recognizable 14,000 foot peaks, Longs Peak.

Two approaches to estimating the effect of climate change on visitation and employment in RMNP were compared. The first approach uses variations in monthly visitation in response to historic variations in temperature. The results of this first approach showed a statistically significant positive effect of temperature on visitation (see Loomis and Richardson (2006) for more details). However, increased visitation slowed as temperatures got hotter and hotter, and visitation even declined during one summer of very high temperatures (60 days over 80 degrees F) by –7.5%.

The second approach uses a survey that portrayed the direct effects (e.g., temperature) and indirect effects (e.g., changes in elk and ptarmigan—an alpine bird, and percent of the park in tundra). Visitors were then asked to indicate if they would change their visits to RMNP or length of stay of the park. The surveys used three climate change scenarios, one produced by the Canadian Climate Center (CCC) indicating a 4 degree F increase in temperature by 2020, a Hadley climate scenario that forecasted a 2°F temperature increase by 2020, and an extreme heat scenario designed to capture very hot future conditions (50 days with temperatures above 80 degrees F, as compared to 3 days currently). All climate change scenarios were used with wildlife models to estimate the increase in elk populations and decrease in ptarmigan populations. The extreme heat survey found similar results to that of the monthly visitation model.

Table 6. Change in Visits, Jobs and Visitor Benefits with Three Climate Change Scenarios

	Annual Visits	% change	Tourism Jobs	Visitor Benefits (Millions)
Current	3,186,323		6,370	$1,004
CCC	3,618,856	13.6%	7,351	$1,216
Hadley	3,502,426	9.9%	7,095	$1,157
Extreme Heat	2,907,520	-8.7%	5,770	$959

Table 6 shows the results of the CCC and Hadley climate scenarios on visitation, visitor benefits and tourism employment as compared to current conditions. The historic visitation model would predict an 11.6% increase in visitation with CCC and 6.8% with Hadley. The visitor survey estimates of visitation change are 13.6% increase with CCC and 9.9% increase with Hadley. Not only is there fairly good agreement between the two methods, but the warmer CCC climate change scenario produces larger increases in visitation.

Amenity Value of Climate

It is well established that preferences for climate affect where people choose to live and work. The desire to live in a mild, sunny climate may reflect health considerations. For example, people with chronic obstructive lung disease or angina may wish to avoid cold winters. Warmer climates may be more pleasant for persons with arthritis. Climate preferences may also reflect the desire to reduce heating and/or cooling costs. Certain climates may be complementary to leisure activities. For example, skiers may wish to live in colder climates, sunbathers in warmer ones. Or a particular climate may simply make life more enjoyable in the course of everyday life. It is also likely that, in addition to preferring certain temperatures and more sunshine, people would like to reduce the risk of experiencing abrupt climate events such as hurricanes and floods.

While climate itself is not bought and sold in markets, the goods that are integral to location decisions—such as housing and jobs—*are* market goods. Consequently, economists look at behavior with regard to location choice (the prices that are paid for houses and the wages that are accepted for jobs) in order to determine how large a role climate plays in these decisions and, therefore, how valuable different climates are to the general public. The remainder of this section discusses methods that have been used to estimate the amenity values people attach to various climate attributes, as well as the value they attach to avoiding extreme weather events. Unfortunately, few studies have rigorously estimated climate amenity values (e.g., the value of a 2°C change in mean January temperature) for the U.S. and then used these values to estimate the dollar value of various climate scenarios.

Valuing Climate Amenities

People's preferences for climate attributes should be reflected in their location decisions. Other things equal, homeowners should be willing to pay more for housing (and so bid up housing prices) in more desirable climates, and so property values should be higher in those climates. Similarly, workers should be willing to accept lower wages to live in more pleasant climates; if climate also affects firms' costs, however, actual wages may rise or fall due to the interaction between firms and workers (Roback, 1982).

Early attempts to estimate how much consumers will pay for more desirable climates start from the view that a good—such as housing or a job—is a bundle of attributes that are valued by the homeowner or worker. The price the consumer pays for the good (such as a house) is actually a composite of the prices that are implicitly paid for all the attributes of the good. Using a statistical technique (known as a hedonic value function), economists can estimate the price of a particular attribute, such as climate. The hedonic property value function, thus, describes how housing prices vary across cities as a function of housing characteristics and locational amenities, such as climate, crime, air quality, or proximity to the ocean. Similarly, the hedonic wage function relates the observed wages to job characteristics (such as occupation and industry), worker characteristics (such as education and years of experience), and locational amenities.

The value of locational amenities—i.e., how much individuals are willing to pay for amenities—can be inferred from these estimated hedonic wage and property value functions. Extracting this value, however, assumes that workers and homeowners are mobile, i.e., that they can choose where to live fairly freely within the U.S. Similarly, it assumes that, in general, individuals have moved to where they would like to live (at the moment), so that housing and job markets are in what is said to be "equilibrium." It also assumes that workers and homeowners have good information about the location to which they are moving, and that sufficient options (in terms of jobs and houses and amenities) are available to them. The estimates of the value of a particular amenity—such as climate—will be more accurate the more nearly these assumptions are met.

A number of hedonic wage and property value studies have included climate, among other variables, in their analyses: by Hoch and Drake (1974); Cropper and Arriaga-Salinas (1980); Cropper (1981); Roback (1982); Smith (1983); Blomquist *et al.* (1988); Gyourko and Tracy (1991). The first four studies estimate only hedonic wage functions, while the last three estimate both wage and property value equations. As Moore (1998) and Gyourko and Tracy (1991) note, this literature suggests that climate amenities are reflected to a greater extent in wages than in property values.[19] Roback (1982), Smith (1983), and Blomquist *et al.* (1988) all find sunshine to be capitalized in wages as an amenity, while heating degree days are capitalized as a disamenity (Roback, 1982, 1988; Gyourko and Tracy, 1991).

More recent studies using the hedonic approach include Moore (1998) and Mendelsohn (2001), who use their results to estimate the value of mean temperature changes in the U.S. associated with future climate scenarios. Moore uses aggregate wage data for Metropolitan Statistical Areas (MSAs) to estimate the responsiveness of wages with respect to climate variables for various occupations. Climate is captured by annual temperature, precipitation and by the difference between average July and average January temperature. Moore estimates that a 4.5°C increase in mean annual temperature would be worth between $30 and $100 billion (1987$) assuming that precipitation and seasonal variation in temperature remain unchanged.

[19] The effect of weather variables on property values is mixed, with Blomquist *et al.* (1988) finding property values to be negatively correlated with precipitation, humidity and heating and cooling degree days, but Roback (1982) finding property values positively correlated with heating degree days. Gyourko and Tracy (1991) find heating and cooling degree days negatively correlated with housing expenditures, but humidity positively correlated.

Mendelsohn (2001) uses county-level data on wages and rents to estimate hedonic wage and property value models. Separate equations are estimated for wages in retail, wholesale, service and manufacturing jobs. Climate variables, which include average January, April, June and October temperature and precipitation, enter each equation in quadratic form. Warmer temperatures are generally associated with lower wages and lower rents, although the former effect is larger in magnitude. Mendelsohn uses the results of these models to estimate the impact of a uniform increase in temperature of 1° C, 2° C and 3.5° C, paired, alternately with an 8% and a 15% increase in precipitation. The results indicate that warming is likely to produce positive benefits in every scenario except the 3.5° C temperature change. Averaging across estimates produced by the 3 models for each of the 6 scenarios suggests annual net benefits (in 1987$) of $25 billion.

Unfortunately, hedonic wage and property value studies have limitations that have caused them to be replaced by alternate approaches to analyzing data on location choices. One drawback of the hedonic approach is that, as mentioned above, it assumes that national labor and housing markets exist and are in equilibrium. As Graves and Mueser (1993) and Greenwood *et al.* (1991) point out, if national markets are not in equilibrium, inferring the value of climate amenities from hedonic wage and property value studies can lead to badly biased results. A second problem is that variables that are correlated with climate (e.g., the availability of recreational facilities) may be difficult to measure; hence, climate variables may pick up their effects. In hedonic property value studies, for example, the use of heating and cooling degree days to measure climate amenities is problematic because their coefficients may capture differences in construction and energy costs as well as climate amenities per se. A related problem in hedonic wage equations is that more able workers may locate in areas with more desirable climates. If ability is not adequately captured in the hedonic wage equation, the coefficients of climate amenities will reflect worker ability as well as the value of climate.

Cragg and Kahn (1997) were the first to relax the national land and labor market equilibrium assumption by estimating a discrete location choice model. Using Census data, they model the location decisions of people in the U.S. who moved between 1975 and 1980. Movers compare the utility they would receive from living in different states—which depends on the wage they would earn and on the cost of housing, as well as on climate amenities—and are assumed to choose the state that yields the highest utility. This allows Cragg and Kahn to estimate the parameters of individuals' utility functions and thus infer the rate at which they will trade income for climate amenities.

The drawback of this study is that it estimates the preferences of movers, who may differ from the general population. An alternate approach (Bayer *et al.*, 2006; Bayer and Timmins, 2005) is to acknowledge that moving is costly and to explain the location decisions of all households, assuming that all households are in equilibrium, given moving costs. Unfortunately, the discrete choice literature has yet to provide reliable estimates of the value of climate amenities in the U.S.

Valuing Hurricanes, Flood and Extreme Weather Events

It is sometimes suggested that the value people place on avoiding extreme weather events can be measured by the damages that such events cause, or by the premiums that people pay for flood or disaster insurance. *Ex post* losses associated with extreme weather events represent a lower bound to the value people place on avoiding these events, as long as people are risk averse. It is also the case that people can purchase insurance only against the monetary losses associated with floods and hurricanes; hence, insurance premiums will not capture the entire value placed on avoiding these events.

The value of avoiding extreme weather events should be reflected in property values, assuming that people are informed about risks: houses in an area with high probability of hurricane damage should sell for less than comparable houses in an area with a lower chance of hurricane damage, holding other amenities constant. To estimate the value of avoiding these events correctly is, however, tricky; it can be difficult to disentangle (e.g.) hurricane risk (a negative effect) from proximity to the coast (an amenity).

Recent studies use natural experiments to determine the value of avoiding hurricanes and floods. Hallstrom and Smith (2005) use property value data before and after hurricane Andrew in Lee County, a county that did not suffer damage from the hurricane, to determine the impact of hurricane risk on property values. They find that property values in special flood hazard areas of Lee County declined by 19% after hurricane Andrew. The magnitude of this decline is significant, and agrees with Bin and Polasky (2004). Bin and Polasky find that housing values in a flood plain in North Carolina declined significantly after hurricane Floyd, compared to houses not at risk. For the average house, the decline in price exceeded the present value of premiums for flood insurance, suggesting that the latter are, indeed, a lower bound to the value of avoiding floods.

5.4. Towards a Research Agenda for Human Welfare

The study of the impacts of climate change on human welfare is still developing. Many studies of impacts of on particular sectors—such as health or agriculture—discuss and in some cases quantify effects that have clear implications for welfare. For example, researchers have looked at the mortality associated with heat stroke (described in the health section of this chapter and the health chapter of this report) or the potential effects on jobs and food prices associated with changes in agricultural practices and adaptive responses, such as changes in cultivars or movement northward of farms. Studies also hint at changes that are perhaps less obvious, but also have welfare implications (such as changes in outdoor activity levels and how much time is spent indoors) and point also to effects with far more dramatic consequences (such as breakdown in public services and infrastructure associated with possible extreme events of the magnitude of Katrina). Adaptation, too, has welfare implications that studies do not always point out, such as the costs (financial and psychological) to the individual of changing behavior.

To our knowledge, no study has, however, made a systematic survey of the myriad welfare implications of climate change, much less attempted to quantify—nor yet to aggregate—them. An almost bewildering choice of typologies are available for categorizing effects on quality of life, wellbeing, or human welfare—terms that are often used interchangeably in the literature. The social science and planning literatures provide not only a range of typologies, but also an array of metrics that could be used to measure life quality.

To further dialogue on the topic of human welfare, this chapter explores one commonly used method: the social indicators approach. This approach generally divides welfare effects into broad categories, such as economic conditions or human health, and then identifies subcategories of important effects. The subcategories are then associated with (usually) concrete measures or metrics, by which progress in meeting goals can be measured. It is widely used by researchers, public planners, and the popular press alike, for purposes as prosaic as the informal measures presented in publications like Places Rated Almanac, to more rigorously evaluated and formally derived measures used by researchers and organizations such as the United Nations.

Most of the measures of welfare—including the social indicators approach—focus on individual measures of welfare, although measured at the society level. For example, personal disposable income is an important component of wellbeing, and so analogous measures of welfare at the social level may use per capita income, the distribution of income, or percentage of families or individuals below the poverty level. There is, however, another dimension to welfare—community welfare. Communities represent networks of households, businesses, physical structures, and institutions and so reflect the interdependencies and complex reality of human systems. Understanding how climate impacts communities, and how communities are vulnerable—or can be made more resilient—in the face of climate change, is an important component of understanding welfare.

Regardless of the framework, however, estimating impacts on human welfare involves numerous and diverse effects. This poses several critical difficulties:

- The large number of effects makes the task of linking impacts to climate change—whether qualitatively or quantitatively—difficult.
- The interdependence of physical and human systems further complicates the process of quantification—both for community effects, and also for ecosystems, raising doubts about a piecemeal approach to estimation.
- The diversity of effects raises questions of how to aggregate effects in order to develop a composite measure of welfare or other metrics that can be used for policy purposes.

Economics offers one alternative to address the diversity of impacts: valuing welfare impacts in monetary terms, which can then be summed. Estimating value, however, requires completing a series of links—from projected climate change to quantitative measures of effects on commodities, services, or conditions that are linked to welfare, and then valuing those effects using economic techniques.

This chapter has looked at the climate impacts and economics literature in four areas of welfare effects—human health, ecosystems, recreation, and climate amenities. The results suggest that these areas are in different stages of development, in terms of the information needed to quantify and monetize the effects of climate. Recreation is the most developed in terms of the efforts that economists have put to developing estimates; even in this case, there are only two comprehensive studies of the effects of climate on recreation in the US that were identified. Health is the most developed of these sectors in terms of the depth of understanding of linkages between climate and health; however few studies examine only the direction but also the magnitude of health effects, and no effort has been made to apply the well-developed (but often controversial) economic methods for valuing mortality and morbidity. While the impact of disaster insurance. *Ex post* losses associated with extreme weather events represent a lower bound to the value people place on avoiding these events, as long as people are risk averse. It is also the case that people can purchase insurance only against the monetary losses associated with floods and hurricanes; hence, insurance premiums will not capture the entire value placed on avoiding these events.

The value of avoiding extreme weather events should be reflected in property values, assuming that people are informed about risks: houses in an area with high probability of hurricane damage should sell for less than comparable houses in an area with a lower chance of hurricane damage, holding other amenities constant. To estimate the value of avoiding these events correctly is, however, tricky; it can be difficult to disentangle (e.g.) hurricane risk (a negative effect) from proximity to the coast (an amenity).

Recent studies use natural experiments to determine the value of avoiding hurricanes and floods. Hallstrom and Smith (2005) use property value data before and after hurricane Andrew in Lee County, a county that did not suffer damage from the hurricane, to determine the impact of hurricane risk on property values. They find that property values in special flood hazard areas of Lee County declined by 19% after hurricane Andrew. The magnitude of this decline is significant, and agrees with Bin and Polasky (2004). Bin and Polasky find that housing values in a flood plain in North Carolina declined significantly after hurricane Floyd, compared to houses not at risk. For the average house, the decline in price exceeded the present value of premiums for flood insurance, suggesting that the latter are, indeed, a lower bound to the value of avoiding floods.

5.4. Towards a Research Agenda for Human Welfare

The study of the impacts of climate change on human welfare is still developing. Many studies of impacts of on particular sectors—such as health or agriculture—discuss and in some cases quantify effects that have clear implications for welfare. For example, researchers have looked at the mortality associated with heat stroke (described in the health section of this chapter and the health chapter of this report) or the potential effects on jobs and food prices associated with changes in agricultural practices and adaptive responses, such as changes in cultivars or movement northward of farms. Studies also hint at changes that are perhaps less obvious, but also have welfare implications (such as changes in outdoor activity levels and how much time is spent indoors) and point also to effects with far more dramatic consequences (such as breakdown in public services and infrastructure associated with possible extreme events of the magnitude of Katrina). Adaptation, too, has welfare implications that studies do not always point out, such as the costs (financial and psychological) to the individual of changing behavior.

To our knowledge, no study has, however, made a systematic survey of the myriad welfare implications of climate change, much less attempted to quantify—nor yet to aggregate—them. An almost bewildering choice of typologies are available for categorizing effects on quality of life, wellbeing, or human welfare—terms that are often used interchangeably in the literature. The social science and planning literatures provide not only a range of typologies, but also an array of metrics that could be used to measure life quality.

Appendix 1:
Chapter 4: Human Welfare
Economic Valuation: An Introduction to Techniques and Challenges

Assessments of the benefits and costs, whether explicit or tacit, underlies all discussion and debates over alternative actions regarding climate change. These assessments are frequently used to inform such questions as: What actions are justified to ease adaptation to changing climate? Or how much are we willing to pay to reduce emissions? (Jacoby, 2003). Ideally, such analyses would be undertaken with complete and reliable information on benefits, converted into a common unit, commensurable with costs and with each other (Jacoby, 2003). In reality, however, while many impacts can be valued, some linkages from climate change to welfare effects are difficult to quantify, much less value. This appendix describes the steps in developing a benefits estimate, and the tools that economists have available for monetizing benefits. It also briefly discusses some of the challenges in monetizing benefits, and weaknesses in the approach.

Estimating the Effects of Climate Change

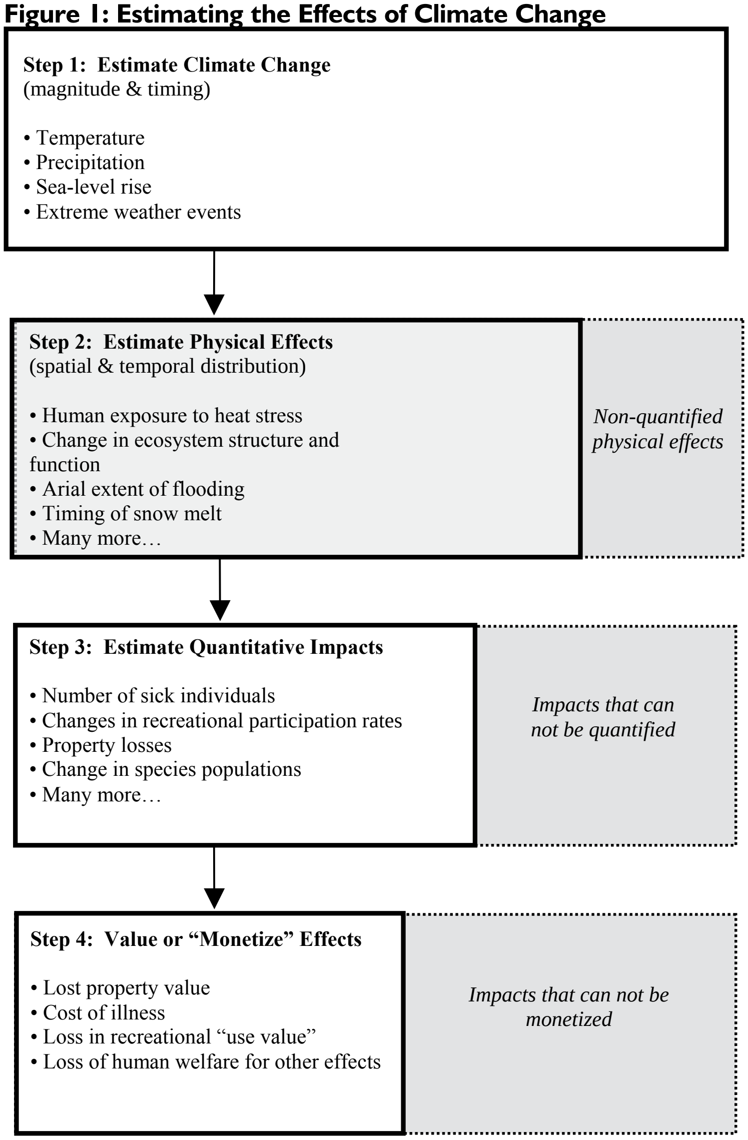
The process of estimating the effects of climate change, including effects on human welfare, involves up to four steps, illustrated in Figure 1. The first step is to estimate the change in relevant measures of climate, including temperature, precipitation, sea-level rise, and the frequency and severity of extreme events. This step is usually accomplished by atmospheric scientists - some form of global circulation model (GCM) is typically deployed. Some analyses stop after this step.

The second step involves estimating the physical effects of those changes in climate in terms of qualitative changes in human and natural systems. These might include changes in ecosystem structure and function, human exposures to heat stress, changes in the geographic range of disease vectors, melting of snow on ski slopes, or flooding of coastal areas. A wide range of disciplines might be involved in carrying our those analyses, deploying an equally wide range of tools. Many analyses are complete once this step is completed - for example, we may be unable to say anything more than that increases in precipitation will change an ecosystem's function.

The third step involves translating the physical effects of changes in climate into metrics indicating quantitative impacts. If the ultimate goal is monetization, ideally these measures should be amenable to valuation. Examples include quantifying the number and location of properties that are vulnerable to floods, estimating the number of individuals exposed to and sensitive to heat stress, or estimating the effect of diminished migratory bird populations on bird-watching participation rates. Many analyses that reach this step in the process, but not all, also proceed on to the fourth step.

The fourth step involves valuing or monetizing the changes. The simplest approach would be to apply a unit valuation approach; for example, the cost of treating a nonfatal case of heat stress or malaria attributable to climate change is a first approximation of the value of avoiding that case altogether. In many contexts, however, unit values can misrepresent the true marginal economic impact of these changes. For example, if climate change reduces the length of the ski season, individuals could engage in another recreational activity, such as golf. Whether they might prefer skiing to golf at that time and location is something economists might try to measure.

Figure 1: Estimating the Effects of Climate Change



This step-by-step linear approach to effects estimation is sometimes called the "damage function" approach. One practical advantage of the damage function approach is the separation of disciplines—scientists can complete their work in steps 1 and 2, and sometimes in step 3, and then economists do their work in step 4. The linear process can work well in cases where individuals respond and change their behavior in response to changes in their environment, without any "feedback" loop.

The linear approach is not always appropriate, however. A damage function approach might imply that we look at effects of climate on human health as separate and independent from effects on ecology and recreation, but at some level they are inter-related, as health care and recreation both require resources in the form of income. In addition, responding to heat stress by installing air conditioning leads to higher energy demand, which in turn may increase greenhouse gas emissions and therefore contribute to further climate change. Recent research suggests that the damage function approach, under some conditions, may be both overly simplistic (Freeman, 2003) and subject to serious errors (Strzepek *et al.*, 1999; Strzepek and Smith, 1995).

Monetizing and Valuing Non-Market Goods

Economists have developed a suite of methods to estimate willingness to pay for non-market goods (see text for a discussion of the market vs. non-market distinction). These methods can be grouped into two broad categories, based largely on the source of the data: revealed preference and stated preference approaches (Freeman, 2003; U.S. EPA, 2000). Revealed preference, sometimes referred to as the indirect valuation approach, involves inferring the value of a non-market good using data from market transactions. For example, a lake may be valued for its ability to provide a good fishing experience. This value can be estimated by the time and money expended by the angler to fish at that particular site, relative to all other possible fishing sites. Or, the amenity value of a coastal property that is protected from storm damage (by a dune, perhaps) can be estimated by comparing the price of that property to other properties similar in every way but the enhanced storm protection.

Stated And Revealed Preference Approaches

Accurate measurement of the non-market amenity of interest, in a manner that is not inconsistent with the way market participants perceive the amenity, is critical to a robust estimate of value.

Revealed preference approaches include recreational demand models, which estimate the value of recreational amenities through time and money expenditures to enjoy recreation; hedonic wage and hedonic property value models, which attempt to isolate the value of particular amenities of property and jobs not themselves directly traded in the marketplace based on their price or wage outcomes; and averting behavior models, which estimate the value of time or money expended to avert a particular bad outcome as a measure of its negative effect on welfare.

Stated preference approaches, sometimes referred to as ***direct valuation*** approaches, are survey methods that estimate the value individuals place on particular non-market goods based on choices they make in hypothetical markets.[20] The earliest stated preference studies involved simply asking individuals what they would be willing to pay for a particular non-market good. The best studies involve great care in constructing a credible, though still hypothetical, trade-off between money and the non-market good of interest to discern individual preferences for that good and hence, willingness to pay (WTP). For example, economists might construct a hypothetical choice between multiple housing locations, each of which differs along the dimensions of price and health risk. Repeated choice experiments of this type ultimately map out the individual's tradeoff between money and the non-market good. The major challenges in stated preference methods involve study design, particularly the construction of a reasonable and credible market for the good, and estimation of a valuation function from the response data.

[20] The contingent valuation method (CVM), or a modern variants, a stated choice model (SCM), are forms of the stated preference methods.

In theory, if individuals understand the full implications of their market choices, in real or constructed markets, then both revealed and stated preference approaches are capable of providing robust estimates of the total value of non-market goods. When considering the complex and multidimensional implications of climate change in the application of revealed and stated preference approaches, it can be extraordinarily challenging to ensure that individuals are sufficiently informed that their observed or stated choices truly reflect their preferences for a particular outcome. As a result, these methods are most often applied to a narrowly defined non-market good, rather than to a complex bundle of non-market goods that might involve multiple tradeoffs and synergistic or antagonistic effects that would be difficult to disentangle.

In addition to market or non-market goods that reflect some use of the environment, value can arise even if a good or service is not explicitly consumed, or even experienced. For example, very few individuals would value a polar bear for its ability to provide sustenance - those who do might not express that value through a direct market for polar bear meat, but by hunting for the bear. Whether through a market or in a non-market activity, those individuals have value for a consumptive use—once enjoyed, that good is no longer available to others to enjoy. In addition to the consumptive users, a small but somewhat larger number of individuals might travel to the Arctic to see a polar bear in its natural environment. These individuals would likely express a value for polar bears, and their "use" of the bear is non-consumptive, but in some sense it does nonetheless affect others ability to view the bear—if too many individuals attempt to view the bears, the congestion might cause the bears to become frightened or, worse, domesticated, diminishing the experience of viewing them.

A third, perhaps much larger group of individuals will never travel to see a polar bear in the flesh. But many individuals in this group would experience some diminishment in their overall quality of life if they knew that polar bears had become extinct. This concept is called "***non-use value***". Although there are several categories of non-use value - some individuals may wish to preserve the future option to visit the Arctic and see a bear, others to bequeath a world with polar bears to future generations, and others might value the mere existence of the bears out of a sense of environmental stewardship. While not all economists agree that non-use values ought to be relevant to policy decisions (Diamond and Hausman, 1993), there is broad agreement that they are difficult to measure, because the expression of non-use values does not result in measurable economic behavior (that is, there is no "use" expressed). Those that recognize non-use values acknowledge that they are likely to be of greatest consequence where a resource has a uniqueness or specialness and loss or injury is irreversible, for example in the global or local extinction of a species, or the distribution of a unique ecological resource (Freeman, 2003).

Other Methods of Monetizing

Analysts can employ other non-market valuation methods: avoided cost or replacement cost, and input value estimates. These methods do not measure willingness to pay as defined in welfare economic terms, but because the methods are relatively straightforward to apply and the results often have a known relationship to willingness to pay, they provide insights into non-market values. This chapter focuses on willingness to pay measures, but recognizes that alternative methods may provide insights and sometimes be more manageable (or appropriate) to estimate a particular non-market value, given data constraints and the limitations imposed by available methods.

Cost of illness studies estimate the change in health expenditures resulting from the change in incidence of a given illness. Direct costs of illness include costs for hospitalization, doctors' fees, and medicine, among others. Indirect costs of illness include effects such as lost work and leisure time. Complete cost of illness estimates reflect both direct and indirect costs. Even the most complete cost of illness estimates, however, typically underestimate willingness to pay to avoid incidence of illness, because they ignore the loss of welfare associated with pain and suffering and may not reflect costs of averting behaviors the individuals have taken to avoid the illness. Some studies suggest that the difference between cost of illness and willingness to pay can be large, but the difference varies greatly across health effects and individuals (U.S. EPA, 2000).

Replacement cost studies approach non-market values by estimating the cost to replace the services provided to individuals by the non-market good. For example, healthy coastal wetlands may provide a wide range of services to individuals who live near them; they may filter pollutants present in water; absorb water in times of flood; act as a buffer to protect properties from storm surges; provide nursery habitat for recreational and commercial fish; and provide amenities in the form of opportunities to view wildlife. A replacement cost approach would estimate the value of these services by estimating market costs for treating contaminants, containing floods, providing fish from hatcheries, or perhaps restoring an impaired wetland to health.

The replacement cost approach is limited in three important ways: 1) the cost of replacing a resource does not necessarily bear any relation to the welfare enhancing effect of the resource; 2) as resources grow scarce, we would expect their value would be underestimated by an average replacement cost; 3) Complete replacement of ecological systems and services may be highly problematic. Replacement cost studies are most informative in those conditions where loss of the resource would certainly and without exception trigger the incidence of replacement costs - in reality, those conditions are not as common as they might seem, because in most cases there are readily available substitutes for those services, even if accessing them involves incurring some transition costs.

Finally, value can also be calculated using the contribution of the resource as an input into a productive process. This approach can be used for both market and non-market inputs. For example, it can be used to estimate the value of fertilizer, as well as water or soil, in farm output and profits. An ecosystem's service input into a productive process could, in theory, be used in this same way.

Issues in Valuation and Aggregation

The topic of issues in valuation is far larger than can be covered here. We focus only on identifying in a superficial way a few of the most important issues, in the context of climate change.

B virtue of the simple process of aggregation, the economic approach creates some difficulties. These difficulties are not specific to the economic approach, however; any method of aggregation would face the same limitations.

- Aggregation, by balancing out effects to produce a “net” effect, masks the positive and negative effects that comprise net effects, hides inequities in the distribution of impacts, or large negative impacts that fall on particular regions or vulnerable populations.
- Any method of aggregation must make an explicit assumption about how to aggregate over time, i.e., whether to weight future benefits the same as current benefits (economic analyses generally discount the future, i.e., weight it less heavily in decision making than the present, for a number of reasons)
- The method of putting diverse impacts on the same yardstick ignores differences in how we may wish to treat these impacts from a policy perspective, and assumes that all impacts are equally certain or uncertain, despite differences in estimation and valuation methods. These differences may be particularly apparent, for example, for non-market and market goods.

Several potential criticisms of the economic approach in the context of climate change relate more directly to how economists approach the task of valuation. One issue is the assumption of stability of preferences over time. Economic studies conducted today, whether revealed or stated preference, reflect the actions and preferences of individuals today, expressed in today’s economic, social, and technological context. For an issue such as climate change, however, impacts may occur decades or centuries hence. The valuation of impacts that occur in the future should depend on preferences in the future. For the most part, however, while there are some rudimentary ways in which economists model changes in technology or income, there is no satisfactory means of modeling changes in preferences over time.

A second issue is the treatment of uncertainty. Economic analysis under conditions of imperfect information and uncertainty is possible, but is one of the most difficult undertakings in economics. While some climate change impacts may be relatively straight-forward, valuation of many climate change impacts requires analysis and use of welfare measures that incorporate uncertainty. When imperfect information prevails, the valuation measure must factor in errors that arise because of it, and when risk or uncertainty prevail, the most commonly used valuation measure is the option price. Two related concepts are option value, and expected consumer’s surplus. All three concepts are more complicated than the discussion here can do justice to, but briefly:

- Expected consumer’s surplus, E[CS] is just consumer’s surplus (CS), or value in welfare terms, weighted by the probabilities of outcomes that yield CS. For example, if a hiker gets $5 of CS per year in a “dry” forest and $10 in a wet forest (one that is greener) and the probability of the forest being dry is 0.40 and of it being wet is 0.60, then the E[CS] = 0.40 X $5 + 0.60 X $10. Expected consumer’s surplus is really an ex-post concept, because we must know CS in each state after it occurs.
- Option price (OP) is the WTP that balances expected utility (utility weighted by the probabilities of outcomes) with and without some change. It is a measure of WTP the individual must express before outcomes can be known with certainty, i.e. a true ex ante welfare measure. For example, the hiker might be willing to pay $8 per year to balance

her expected utility with conditions being wet, versus conditions being dry. The $8 might be a payment to support a reduction in dryness otherwise due to climate change.

- Option value (OV) is the difference between OP and E[CS]. A related concept is called quasi-option value and pertains to the value of waiting to get more information.

A third issue concerns behavioral paradoxes. Most economic analyses, particularly if they involve uncertain or risky outcomes, require rationality in the expression of preferences. Such basic axioms as treating gains and losses equally, reacting to a series of small incremental gains with equal strength to a single large gain of the same aggregate magnitude, and viewing gains and losses from an absolute rather than relative or positional scale are particularly important to studies that rely on expected utility theory - that individuals gain and lose welfare in proportion to the product of the likelihood of the gain or loss and its magnitude. Several social and psychological science studies, however, suggest that under many conditions individuals do not behave in a manner consistent with this definition of rationality. For example, prospect theory, often credited as resulting from the work of Daniel Kahneman and Amos Tversky, suggests that behavior under risk or uncertainty is better explained both by reference to a status quo reference point and acknowledgement of unequal treatment of risk aversion when considering losses and gains, even when it can be shown that a different behavior would certainly make the individual better off.

Finally, the issue of perspective—“whose lens are we looking through"—is critical to welfare analysis, particularly economic welfare. In health policy, for example, thinking about whether it is worthwhile to invest in mosquito netting to control malaria depends on whether you are at CDC, at a health insurer, or are an individual in a place where malaria risk is high. In general, the perspective of valuation focuses on the valuation of individuals who are directly affected, and who are living today. The perspectives of public decision makers may be somewhat different from those of individuals, since they will take into account social and community consequences, as well as individual consequences.

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Synthesis and Assessment Product 4.6
Appendix 1. Glossary

Source: Derived from Intergovernmental Panel on Climate Change
Third Assessment Report, Working Group II

A

Acclimatization
The physiological adaptation to climatic variations.

Adaptability
See *Adaptive capacity*.

Adaptation
Adjustment in natural or *human systems* to a new or changing environment. Adaptation to *climate change* refers to adjustment in natural or human systems in response to actual or expected climatic *stimuli* or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.

Adaptation assessment
The practice of identifying options to adapt to *climate change* and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.

Adaptation benefits
The avoided damage costs or the accrued benefits following the adoption and *implementation* of *adaptation* measures.

Adaptation costs
Costs of planning, preparing for, facilitating, and implementing *adaptation* measures, including transition costs.

Adaptive capacity
The ability of a system to adjust to *climate change* (including *climate variability* and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Aggregate impacts
Total impacts summed up across sectors and/or regions. The aggregation of impacts requires knowledge of (or assumptions about) the relative importance of impacts in different sectors and regions. Measures of aggregate impacts include, for example, the total number of people affected, change in net primary productivity, number of systems undergoing change, or total economic costs.

Albedo
The fraction of *solar radiation* reflected by a surface or object, often expressed as a percentage. Snow covered surfaces have a high albedo; the albedo of soils ranges from high to low; vegetation covered surfaces and oceans have a low albedo. The Earth's albedo varies mainly through varying cloudiness, snow, ice, leaf area, and land cover changes.

Ancillary benefits
The ancillary, or side effects, of policies aimed exclusively at *climate change mitigation*. Such policies have an impact not only on *greenhouse gas emissions*, but also on resource use efficiency, like reduction in emissions of local and regional air pollutants associated with *fossil-fuel* use, and on issues such as transportation, agriculture, *land-use* practices, employment, and fuel security. Sometimes these benefits are referred to as "ancillary impacts" to reflect that in some cases the benefits may be negative. From the perspective of policies directed at abating

local air pollution, greenhouse gas mitigation may also be considered an ancillary benefit, but these relationships are not considered in this assessment.

Anthropogenic

Resulting from or produced by human beings.

Anthropogenic emissions

Emissions of *greenhouse gases*, greenhouse gas *precursors*, and *aerosols* associated with human activities. These include burning of *fossil fuels* for energy, *deforestation*, and *land-use* changes that result in net increase in emissions.

Arid regions

Ecosystems with less than 250 mm precipitation per year.

Atmosphere

The gaseous envelop surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% *volume mixing ratio*) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium, and radiatively active *greenhouse gases* such as *carbon dioxide* (0.035% volume mixing ratio) and *ozone*. In addition, the atmosphere contains water vapor, whose amount is highly variable but typically 1% volume mixing ratio. The atmosphere also contains clouds and *aerosols*.

B

Baseline

The baseline (or reference) is any datum against which change is measured. It might be a "current baseline," in which case it represents observable, present-day conditions. It might also be a "future baseline," which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

C

Carbon dioxide (CO2)

A naturally occurring gas, and also a by-product of burning *fossil fuels* and *biomass*, as well as *land-use changes* and other ndustrial processes. It is the principal *anthropogenic greenhouse gas* that affects the Earth's *radiative balance*. It is the reference gas against which other greenhouse gases are measured and has a *Global Warming Potential* of 1.

Cholera

An intestinal infection that results in frequent watery stools, cramping abdominal pain, and eventual collapse from dehydration.

Climate

Climate in a narrow sense is usually defined as the "average weather" or more rigorously as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*.

Climate change

Climate change refers to a statistically significant variation in either the mean state of the *climate* or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or *external forcings*, or to persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use*. Note that the *United Nations Framework Convention on Climate Change* (UNFCCC), in its Article 1, defines "climate change" as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” The UNFCCC thus makes a distinction between “climate change” attributable to human activities altering the atmospheric composition, and “climate variability” attributable to natural causes. See also *climate variability*.

Climate model (hierarchy)

A numerical representation of the *climate system* based on the physical, chemical, and biological properties of its components, their interactions and *feedback* processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity—that is, for any one component or combination of components a “hierarchy” of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical *parametrizations* are involved. Coupled atmosphere/ocean/sea-ice *general circulation models* (AOGCMs) provide a comprehensive representation of the climate system. There is an evolution towards more complex models with active chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal, and interannual *climate predictions*.

Climate prediction

A climate prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the *climate* in the future (e.g., at seasonal, interannual, or long-term *time-scales*). See also *climate projection* and *climate (change) scenario*.

Climate projection

A *projection* of the response of the *climate system* to *emission* or concentration *scenarios* of *greenhouse gases* and *aerosols*, or *radiative forcing scenarios*, often based upon simulations by *climate models*. Climate projections are distinguished from *climate predictions* in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socio-economic and technological developments that may or may not be realized, and are therefore subject to substantial *uncertainty*.

Climate scenario

A plausible and often simplified representation of the future *climate*, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of *anthropogenic climate change*, often serving as input to impact models. *Climate projections* often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A “climate change scenario” is the difference between a climate scenario and the current climate.

Climate system

The climate system is the highly complex system consisting of five major components: the *atmosphere*, the *hydrosphere*, the *cryosphere*, the land surface and the *biosphere*, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and human-induced forcings such as the changing composition of the atmosphere and *land-use change*.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the *climate* on all *temporal and spatial scales* beyond that of individual weather events. Variability may be due to natural internal processes within the *climate system* (internal variability), or to variations in natural or *anthropogenic external forcing* (external variability). See also *climate change*.

Co-benefits

The benefits of policies that are implemented for various reasons at the same time—including *climate change mitigation*— acknowledging that most policies designed to address *greenhouse gas mitigation* also have other, often at least equally important, rationales (e.g., related to objectives of development, sustainability, and equity). The term co-impact is also used in a more generic sense to cover both the positive and negative sides of the benefits. See also *ancillary benefits*.

Cooling degree days

The integral over a day of the temperature above 18°C (e.g., a day with an average temperature of 20°C counts as 2 cooling degree days). See also *heating degree days*.

Coping range

The variation in climatic *stimuli* that a system can absorb without producing significant impacts.

Cost-effective

A criterion that specifies that a *technology* or measure delivers a good or service at equal or lower cost than current practice, or the least-cost alternative for the achievement of a given target.

D

Dengue Fever

An infectious viral disease spread by mosquitoes often called breakbone fever because it is characterized by severe pain in joints and back. Subsequent infections of the virus may lead to dengue hemorrhagic fever (DHF) and dengue shock syndrome (DSS), which may be fatal.

Desert

An *ecosystem* with less than 100 mm precipitation per year.

Desertification

Land degradation in arid, *semi-arid*, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Further, the United Nations Convention to Combat Desertification defines land degradation as a reduction or loss in arid, semi-arid, and dry sub-humid areas of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, *forest*, and woodlands resulting from *land uses* or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil *erosion* caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.

Detection and attribution

Climate varies continually on all *time scales*. Detection of *climate change* is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Disturbance regime

Frequency, intensity, and types of disturbances, such as fires, inspect or pest outbreaks, floods, and *droughts*.

Diurnal temperature range

The difference between the maximum and minimum temperature during a day.

Drought

The phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems.

E

Ecosystem

A system of interacting living organisms together with their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small *spatial scales* to, ultimately, the entire Earth.

Ecosystem services

Ecological processes or functions that have *value* to individuals or society.

El Niño Southern Oscillation (ENSO)

El Niño, in its original sense, is a warm water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the intertropical surface pressure pattern and circulation in the Indian and Pacific Oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño Southern Oscillation, or ENSO. During an El Niño event, the prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The opposite of an El Niño event is called *La Niña*.

Emissions

In the *climate change* context, emissions refer to the release of *greenhouse gases* and/or their *precursors* and *aerosols* into the *atmosphere* over a specified area and period of time.

Endemic

Restricted or peculiar to a locality or region. With regard to human health, endemic can refer to a disease or agent present or usually prevalent in a population or geographical area at all times.

Epidemic

Occurring suddenly in numbers clearly in excess of normal expectancy, said especially of *infectious diseases* but applied also to any disease, injury, or other health-related event occurring in such outbreaks.

Eutrophication

The process by which a body of water (often shallow) becomes (either naturally or by pollution) rich in dissolved nutrients with a seasonal deficiency in dissolved oxygen.

Evaporation

The process by which a liquid becomes a gas.

Evapotranspiration

The combined process of *evaporation* from the Earth's surface and *transpiration* from vegetation.

Exotic species

See *introduced species*.

Exposure

The nature and degree to which a system is exposed to significant climatic variations.

Externality

See *external cost*.

External cost

Used to define the costs arising from any human activity, when the agent responsible for the activity does not take full account of the impacts on others of his or her actions. Equally, when the impacts are positive and not accounted for in the actions of the agent responsible they are referred to as external benefits. *Emissions* of particulate pollution from a power station affect the health of people in the vicinity, but this is not often considered, or is given inadequate weight, in private decision making and there is no market for such impacts. Such a phenomenon is referred to as an "externality," and the costs it imposes are referred to as the external costs.

Extinction

The complete disappearance of an entire species.

Extirpation

The disappearance of a species from part of its range; local extinction.

Extreme weather event

An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called extreme weather may vary from place to place. An extreme *climate* event is an average of a number of weather events over a certain period of time, an average which is itself extreme (e.g., rainfall over a season).

G

General circulation

The large scale motions of the *atmosphere* and the ocean as a consequence of differential heating on a rotating Earth, aiming to restore the *energy balance* of the system through transport of heat and momentum.

General Circulation Model (GCM)

See *climate model*.

Global surface temperature

The global surface temperature is the area-weighted global average of (i) the sea surface temperature over the oceans (i.e., the sub-surface bulk temperature in the first few meters of the ocean), and (ii) the surface air temperature over land at 1.5 m above the ground.

Greenhouse effect

Greenhouse gases effectively absorb *infrared radiation*, emitted by the Earth's surface, by the *atmosphere* itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus greenhouse gases trap heat within the surface-troposphere system. This is called the "natural greenhouse effect." Atmospheric radiation is strongly coupled to the temperature of the level at which it is emitted. In the *troposphere,* the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, -19°C, in balance with the net incoming *solar radiation*, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a *radiative forcing*, an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system. This is the "enhanced greenhouse effect."

Greenhouse gas

Greenhouse gases are those gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specific wavelengths within the spectrum of *infrared radiation* emitted by the Earth's surface, the atmosphere, and clouds. This property causes the *greenhouse effect*. Water vapor (H2O), *carbon dioxide* (CO2), *nitrous oxide* (N2O), *methane* (CH4), and *ozone* (O3) are the primary greenhouse gases in the Earth's atmosphere. Moreover there are a number of entirely human-made greenhouse gases in the atmosphere, such as the *halocarbons* and other chlorine- and bromine-containing substances, dealt with under the *Montreal Protocol*. Besides CO2, N2O, and CH4, the *Kyoto Protocol* deals with the greenhouse gases *sulfur hexafluoride* (SF6), *hydrofluorocarbons* (HFCs), and *perfluorocarbons* (PFCs).

H

Habitat

The particular environment or place where an organism or species tend to live; a more locally circumscribed portion of the total environment.

Heat island

An area within an urban area characterized by ambient temperatures higher than those of the surrounding area because of the absorption of solar energy by materials like asphalt.

Heating degree days

The integral over a day of the temperature below 18°C (e.g., a day with an average temperature of 16°C counts as 2 heating degree days). See also *cooling degree days*.

Human settlement

A place or area occupied by settlers.

Human system

Any system in which human organizations play a major role. Often, but not always, the term is synonymous with "society" or "social system" (e.g., agricultural system, political system, technological system, economic system).

I

Ice sheet

A mass of land ice that is sufficiently deep to cover most of the underlying bedrock topography, so that its shape is mainly determined by its internal dynamics (the flow of the ice as it deforms internally and slides at its base). An ice sheet flows outward from a high central plateau with a small average surface slope. The margins slope steeply, and the ice is discharged through fast-flowing ice streams or outlet *glaciers*, in some cases into the sea or into *ice shelves* floating on the sea. There are only two large ice sheets in the modern world, on Greenland and Antarctica, the Antarctic ice sheet being divided into East and West by the Transantarctic Mountains; during glacial periods there were others.

Ice shelf

A floating *ice sheet* of considerable thickness attached to a coast (usually of great horizontal extent with a level or gently undulating surface); often a seaward extension of ice sheets.

(Climate) Impact assessment

The practice of identifying and evaluating the detrimental and beneficial consequences of *climate change* on natural and *human systems*.

(Climate) Impacts

Consequences of *climate change* on natural and *human systems*. Depending on the consideration of *adaptation*, one can distinguish between potential impacts and residual impacts. Potential impacts: All impacts that may occur given a projected change in *climate*, without considering adaptation. Residual impacts: The impacts of climate change that would occur after adaptation. See also a*ggregate impacts*, *market impacts*, and *non-market impacts*.

Indigenous peoples

People whose ancestors inhabited a place or a country when persons from another culture or ethnic background arrived on the scene and dominated them through conquest, settlement, or other means and who today live more in conformity with their own social, economic, and cultural customs and traditions than those of the country of which they now form a part (also referred to as "native," "aboriginal," or "tribal" peoples).

Industrial Revolution
A period of rapid industrial growth with far-reaching social and economic consequences, beginning in England during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The Industrial Revolution marks the beginning of a strong increase in the use of *fossil fuels* and emission of, in particular, fossil *carbon dioxide*. In this report, the terms "pre-industrial" and "industrial" refer, somewhat arbitrarily, to the periods before and after the year 1750, respectively.

Inertia
Delay, slowness, or resistance in the response of the *climate*, biological, or *human systems* to factors that alter their rate of change, including continuation of change in the system after the cause of that change has been removed.

Infectious diseases
Any disease that can be transmitted from one person to another. This may occur by direct physical contact, by common handling of an object that has picked up infective organisms, through a disease carrier, or by spread of infected droplets coughed or exhaled into the air.

Infrastructure
The basic equipment, utilities, productive enterprises, installations, institutions, and services essential for the development, operation, and growth of an organization, city, or nation. For example, roads; schools; electric, gas, and water utilities; transportation; communication; and legal systems would be all considered as infrastructure.

Integrated assessment
A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework, to evaluate the status and the consequences of environmental change and the policy responses to it.

Introduced species
A species occurring in an area outside its historically known natural range as a result of accidental dispersal by humans (also referred to as "*exotic species*" or "alien species").

Invasive species
An *introduced species* that invades natural *habitats*.

L

La Niña
See *El Niño Southern Oscillation*.

Land use
The total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation).

Land-use change
A change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the *albedo*, *evapotranspiration*, *sources*, and *sinks* of *greenhouse gases*, or other properties of the *climate system*, and may thus have an impact on *climate*, locally or globally.

Landslide
A mass of material that has slipped downhill by gravity, often assisted by water when the material is saturated; rapid movement of a mass of soil, rock, or debris down a slope.

M

Maladaptation
Any changes in natural or *human systems* that inadvertently increase *vulnerability* to

climatic *stimuli*; an *adaptation* that does not succeed in reducing vulnerability but increases it instead.

Malaria
Endemic or *epidemic* parasitic disease caused by species of the genus Plasmodium (protozoa) and transmitted by mosquitoes of the genus Anopheles; produces high fever attacks and systemic disorders, and kills approximately 2 million people every year.

Market barriers
In the context of *mitigation* of *climate change*, conditions that prevent or impede the diffusion of *cost-effective* technologies or practices that would mitigate *greenhouse gas emissions*.

Market-based incentives
Measures intended to use price mechanisms (e.g., taxes and tradable permits) to reduce *greenhouse gas emissions*.

Market impacts
Impacts that are linked to market transactions and directly affect *Gross Domestic Product* (a country's national accounts)—for example, changes in the supply and price of agricultural goods. See also *non-market impacts*.

Mitigation
An *anthropogenic* intervention to reduce the *sources* or enhance the *sinks* of *greenhouse gases*.

Mitigative capacity
The social, political, and economic structures and conditions that are required for effective *mitigation*.

Morbidity
Rate of occurrence of disease or other health disorder within a population, taking account of the age-specific morbidity rates. Health outcomes include chronic disease incidence/prevalence, rates of hospitalization, primary care consultations, disability-days (i.e., days when absent from work), and prevalence of symptoms.

Mortality Rate of occurrence of death within a population within a specified time period; calculation of mortality takes account
of age-specific death rates, and can thus yield measures of life expectancy and the extent of premature death.

N

No-regrets opportunities
See *no-regrets policy*.

No-regret options
See *no-regrets policy*.

No-regrets policy
One that would generate net social benefits whether or not there is *climate change*. No-regrets opportunities for *greenhouse gas emissions* reduction are defined as those options whose benefits such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. No-regrets potential is defined as the gap between the *market potential* and the *socio-economic potential*.

Non-linearity
A process is called "non-linear" when there is no simple proportional relation between cause and effect. The *climate system* contains many such non-linear processes, resulting in a system with a potentially very complex behavior. Such complexity may lead to *rapid climate change*.

Non-market impacts
Impacts that affect *ecosystems* or human welfare, but that are not directly linked to market transactions—for example, an increased risk of premature death. See also *market impacts*.

North Atlantic Oscillation (NAO)
The North Atlantic Oscillation consists of opposing variations of barometric pressure near Iceland and near the Azores. On

average, a westerly current, between the Icelandic low pressure area and the Azores high pressure area, carries cyclones with their associated frontal systems towards Europe. However, the pressure difference between Iceland and the Azores fluctuates on *time scales* of days to decades, and can be reversed at times. It is the dominant mode of winter *climate variability* in the North Atlantic region, ranging from central North America to Europe.

O

Ocean conveyor belt
The theoretical route by which water circulates around the entire global ocean, driven by wind and the *thermohaline circulation*.

Opportunity
An opportunity is a situation or circumstance to decrease the gap between the *market potential* of any *technology* or practice and the *economic potential*, *socio-economic potential*, or *technological potential*.

Opportunity costs
The cost of an economic activity forgone by the choice of another activity.

Ozone (O3)
Ozone, the triatomic form of oxygen (O3), is a gaseous atmospheric constituent. In the *troposphere* it is created both naturally and by photochemical reactions involving gases resulting from human activities (photochemical "smog"). In high concentrations, tropospheric ozone can be harmful to a wide-range of living organisms. Tropospheric ozone acts as a *greenhouse gas*. In the *stratosphere*, ozone is created by the interaction between solar ultraviolet radiation and molecular oxygen (O2). Stratospheric ozone plays a decisive role in the stratospheric *radiative balance*. Its concentration is highest in the *ozone layer*. Depletion of stratospheric ozone, due to chemical reactions that may be enhanced by *climate change*, results in an increased ground-level flux of *ultraviolet-B radiation*. See also *Montreal Protocol* and *ozone layer*.

P

Parameterization
In *climate models*, this term refers to the technique of representing processes, that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes), by relationships between the area- or time-averaged effect of such sub-grid-scale processes and the larger scale flow.

Pareto criterion/Pareto optimum
A requirement or status that an individual's welfare could not be further improved without making others in the society worse off.

Permafrost
Perennially frozen ground that occurs wherever the temperature remains below 0°C for several years.

Point-source pollution
Pollution resulting from any confined, discrete source, such as a pipe, ditch, tunnel, well, container, concentrated animal feeding operation, or floating craft. See also *non-point-source pollution*.

Present value cost
The sum of all costs over all time periods, with future costs discounted.

Projection (generic)
A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from "predictions" in order to emphasize that projections involve assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized, and are therefore subject to

substantial *uncertainty*. See also *climate projection* and *climate prediction*.

Proxy

A proxy *climate* indicator is a local record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies are tree ring records, characteristics of corals, and various data derived from ice cores.

R

Radiative forcing

Radiative forcing is the change in the net vertical irradiance (expressed in Wm-2) at the *tropopause* due to an internal change or a change in the external forcing of the *climate system*, such as, for example, a change in the concentration of *carbon dioxide* or the output of the Sun. Usually radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values.

Rapid climate change

The *non-linearity* of the *climate system* may lead to rapid *climate change*, sometimes called abrupt events or even surprises. Some such abrupt events may be imaginable, such as a dramatic reorganization of the *thermohaline circulation*, rapid deglaciation, or massive melting of *permafrost* leading to fast changes in the *carbon cycle*. Others may be truly unexpected, as a consequence of a strong, rapidly changing, forcing of a non-linear system.

Reinsurance

The transfer of a portion of primary insurance risks to a secondary tier of insurers (reinsurers); essentially "insurance for insurers."

Relative sea level

Sea level measured by a *tide gauge* with respect to the land upon which it is situated. See also *Mean Sea Level*.

Resilience

Amount of change a system can undergo without changing state.

Response time

The response time or adjustment time is the time needed for the *climate system* or its components to re-equilibrate to a new state, following a forcing resulting from external and internal processes or *feedbacks*. It is very different for various components of the climate system. The response time of the *troposphere* is relatively short, from days to weeks, whereas the *stratosphere* comes into equilibrium on a *time scale* of typically a few months. Due to their large heat capacity, the oceans have a much longer response time, typically decades, but up to centuries or millennia. The response time of the strongly coupled surface-troposphere system is, therefore, slow compared to that of the stratosphere, and mainly determined by the oceans. The *biosphere* may respond fast (e.g., to *droughts*), but also very slowly to imposed changes. See *lifetime* for a different definition of response time pertinent to the rate of processes affecting the concentration of trace gases.

S

Saltwater intrusion/encroachment

Displacement of fresh surface water or ground water by the advance of saltwater due to its greater density, usually in coastal and estuarine areas.

Scenario (generic)

A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of *technology* change, prices) and relationships. Scenarios are neither predictions nor forecasts and sometimes may be based on a "narrative storyline." Scenarios may be derived from *projections*, but are often based on additional information from other sources. See also *SRES scenarios, climate scenario,* and *emission scenarios*.

Sea-level rise

An increase in the mean level of the ocean. Eustatic sea-level rise is a change in global average sea level brought about by an alteration to the volume of the world ocean. *Relative sealevel* rise occurs where there is a net increase in the level of the ocean relative to local land movements. Climate modelers largely concentrate on estimating eustatic sea-level change. *Impact* researchers focus on relative sea-level change.

Seawall

A human-made wall or embankment along a shore to prevent wave *erosion*.

Semi-arid regions

Ecosystems that have more than 250 mm precipitation per year but are not highly productive; usually classified as *rangelands*.

Sensitivity

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related *stimuli*. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to *sea-level rise*). See also *climate sensitivity*.

Sequential decision making

Stepwise decision making aiming to identify short-term strategies in the face of long-term uncertainties, by incorporating additional information over time and making mid-course corrections.

Sequestration

The process of increasing the carbon content of a carbon *reservoir* other than the *atmosphere*. Biological approaches to sequestration include direct removal of *carbon dioxide* from the atmosphere through *land-use change*, *afforestation*, *reforestation*, and practices that enhance soil carbon in agriculture. Physical approaches include separation and disposal of carbon dioxide from flue gases or from processing *fossil fuels* to produce hydrogen- and carbon dioxide-rich fractions and longterm storage in underground in depleted oil and gas reservoirs, coal seams, and saline *aquifers*. See also *uptake*.

Sink

Any process, activity or mechanism that removes a *greenhouse gas*, an *aerosol*, or a *precursor* of a greenhouse gas or aerosol from the *atmosphere*.

Snowpacks

A seasonal accumulation of slow-melting snow.

Social cost

The social cost of an activity includes the *value* of all the *resources* used in its provision. Some of these are priced and others are not. Non-priced resources are referred to as externalities. It is the sum of the costs of these externalities and the priced resources that makes up the social cost. See also *private cost* and *total cost*.

Socio-economic potential

The socio-economic potential represents the level of greenhouse gas *mitigation* that would be approached by overcoming social and cultural obstacles to the use of technologies that are *cost effective*. See also *economic potential*, *market potential*, and *technology potential*.

Source

Any process, activity, or mechanism that releases a *greenhouse gas*, an *aerosol*, or a *precursor* of a greenhouse gas or aerosol into the *atmosphere*.

Southern Oscillation

See *El Niño Southern Oscillation*.

Spatial and temporal scales
Climate may vary on a large range of spatial and temporal scales. Spatial scales may range from local (less than 100,000 km2), through regional (100,000 to 10 million km2) to continental (10 to 100 million km2). Temporal scales may range from seasonal to geological (up to hundreds of millions of years).

SRES scenarios
SRES scenarios are *emissions scenarios* developed by Nakicenovic *et al*. (2000) and used, among others, as a basis for the *climate projections* in the IPCC WGI contribution to the Third Assessment Report (IPCC, 2001a). The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

(Scenario) Family: Scenarios that have a similar demographic, societal, economic, and technical-change *storyline*. Four scenario families comprise the SRES scenario set: A1, A2, B1, and B2.

(Scenario) Group: Scenarios within a family that reflect a consistent variation of the storyline. The A1 scenario family includes four groups designated as A1T, A1C, A1G, and A1B that explore alternative structures of future energy systems.

In the Summary for Policymakers of Nakicenovic *et al* (2000), the A1C and A1G groups have been combined into one "Fossil-Intensive" A1FI scenario group. The other three scenario families consist of one group each. The SRES scenario set reflected in the Summary for Policymakers of Nakicenovic *et al*. (2000) thus consist of six distinct *scenario groups*, all of which are equally sound and together capture the range of uncertainties associated with driving forces and emissions.

Illustrative Scenario: A scenario that is illustrative for each of the six *scenario groups* reflected in the Summary for Policymakers of Nakicenovic *et al*. (2000). They include four revised *scenario markers* for the *scenario groups* A1B, A2, B1, B2, and two additional scenarios for the A1FI and A1T groups. All *scenario groups* are equally sound.

(Scenario) Marker: A scenario that was originally posted in draft form on the SRES website to represent a given *scenario family*. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakicenovic *et al*. (2000). These scenarios have received the closest scrutiny of the entire writing team and via the SRES open process. Scenarios have also been selected to illustrate the other two *scenario groups*.

(Scenario) Storyline: A narrative description of a scenario (or family of scenarios) highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of their evolution.

Stabilization
The achievement of stabilization of atmospheric concentrations of one or more *greenhouse gases* (e.g., *carbon dioxide* or a *CO2-equivalent* basket of greenhouse gases).

Stimuli (climate-related)
All the elements of *climate change*, including mean *climate* characteristics, *climate variability*, and the frequency and magnitude of extremes.

Storm surge
The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from

the tidal variation alone at that time and place.

Storyline

See *SRES scenarios*.

Streamflow

Water within a river channel, usually expressed in m3 sec-1.

Stratosphere

The highly stratified region of the *atmosphere* above the *troposphere* extending from about 10 km (ranging from 9 km in high latitudes to 16 km in the tropics on average) to about 50 km.

Submergence

A rise in the water level in relation to the land, so that areas of formerly dry land become inundated; it results either from a sinking of the land or from a rise of the water level.

Subsidence

The sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion.

Subsidy

Direct payment from the government to an entity, or a tax reduction to that entity, for implementing a practice the government wishes to encourage. *Greenhouse gas emissions* can be reduced by lowering existing subsidies that have the effect of raising emissions, such as subsidies to *fossil-fuel* use, or by providing subsidies for practices that reduce emissions or enhance *sinks* (e.g., for insulation of buildings or planting trees).

Sustainable development

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

T

Technology

A piece of equipment or a technique for performing a particular activity.

Thermal erosion

The *erosion* of ice-rich *permafrost* by the combined thermal and mechanical action of moving water.

Thermal expansion

In connection with sea level, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level.

Thermohaline circulation

Large-scale density-driven circulation in the ocean, caused by differences in temperature and salinity. In the North Atlantic, the thermohaline circulation consists of warm surface water flowing northward and cold deepwater flowing southward, resulting in a net poleward transport of heat. The surface water sinks in highly restricted sinking regions located in high latitudes.

Top-down models

The terms "top" and "bottom" are shorthand for aggregate and disaggregated models. The top-down label derives from how modelers applied macro-economic theory and econometric techniques to historical data on consumption, prices, incomes, and factor costs to model final demand for goods and services, and supply from main sectors, like the energy sector, transportation, agriculture, and industry. Therefore, top-down models evaluate the system from aggregate economic variables, as compared to *bottom-up models* that consider technological options or project specific *climate change mitigation* policies. Some technology data were, however, integrated into top-down analysis and so the distinction is not that clear-cut.

Total cost

All items of cost added together. The total cost to society is made up of both the *external cost* and the *private cost*, which together are defined as *social cost*.

Trade effects
Economic impacts of changes in the purchasing power of a bundle of exported goods of a country for bundles of goods imported from its trade partners. Climate policies change the relative production costs and may change terms of trade substantially enough to change the ultimate economic balance.

Transient climate response
The globally averaged surface air temperature increase, averaged over a 20-year period, centered at the time of CO2 doubling (i.e., at year 70 in a 1% per year compound CO2 increase experiment with a global coupled *climate model*).

Troposphere
The lowest part of the *atmosphere* from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average) where clouds and "weather" phenomena occur. In the troposphere, temperatures generally decrease with height.

Tundra
A treeless, level, or gently undulating plain characteristic of arctic and subarctic regions.

U

Uncertainty
An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) or by qualitative statements (e.g., reflecting the judgment of a team of experts). See Moss and Schneider (2000).

Unique and threatened systems
Entities that are confined to a relatively narrow geographical range but can affect other, often larger entities beyond their range; narrow geographical range points to *sensitivity* to environmental variables, including *climate*, and therefore attests to potential *vulnerability* to *climate change*.

Urbanization
The conversion of land from a natural state or managed natural state (such as agriculture) to cities; a process driven by net rural-to-urban migration through which an increasing percentage of the population in any nation or region come to live in settlements that are defined as "urban centers"

V

Value added
The net output of a sector after adding up all outputs and subtracting intermediate inputs.

Values
Worth, desirability, or utility based on individual preferences. The total value of any resource is the sum of the values of the different individuals involved in the use of the resource. The values, which are the foundation of the estimation of costs, are measured in terms of the willingness to pay (WTP) by individuals to receive the resource or by the willingness of individuals to accept payment (WTA) to part with the resource.

Vector
An organism, such as an insect, that transmits a pathogen from one host to another. See also *vector-borne diseases*.

Vector-borne diseases
Disease that is transmitted between hosts by a *vector* organism such as a mosquito or tick

(e.g., *malaria*, *dengue fever*, and leishmaniasis).

Vulnerability

The degree to which a system is susceptible to, or unable to cope with, adverse effects of *climate change*, including *climate variability* and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its *sensitivity*, and its *adaptive capacity*.

W

Water stress

A country is water-stressed if the available freshwater supply relative to water withdrawals acts as an important constraint on development. Withdrawals exceeding 20% of renewable water supply has been used as an indicator of water stress.

Water-use efficiency

Carbon gain in *photosynthesis* per unit water lost in *evapotranspiration*. It can be expressed on a short-term basis as the ratio of photosynthetic carbon gain per unit transpirational water loss, or on a seasonal basis as the ratio of *net primary production* or agricultural yield to the amount of available water.

Water withdrawal

Amount of water extracted from water bodies.

Z

Zoonotic disease

A disease that normally exists in other vertebrates but also infects humans, such as dengue fever, avian flu, west Nile virus and bubonic plague.