Analyses of the effects of global change on human health and welfare and human systems

THIRD REVIEW DRAFT
FOR CCSP and CENR CLEARANCE—APRIL 2008

Synthesis and Assessment Product 4.6
Report by the U.S. Climate Change Science Program
And the Subcommittee on Global Change Research

TABLE OF CONTENTS

2. Effects of Global Change on Human Health

3. Effects of Global Change on Human Settlements

4. Effects of Global Change on Human Welfare

5. Common Themes and Research Recommendations

Synthesis and Assessment Product 4.6

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

Executive Summary

Convening Lead Author: Janet L. Gamble, U.S. Environmental Protection Agency

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

Contributing Authors: Colleen Reid, ASPH Fellow, John V. Thomas, U.S. Environmental Protection Agency, Christopher P. Weaver, U.S. Environmental Protection Agency, Melinda Harris, ICF International, Randy Freed, ICF International

Table of Contents

Abstract

Climate change, interacting with changes in land use and demographics, will affect important human dimensions in the United States, especially those related to human health, settlements and welfare. The challenges presented by population growth, an aging population, migration patterns, and urban and coastal development will be compounded by changes in temperature, precipitation, and extreme climate-related events. Climate change will affect where people choose to live, work, and play. Among the most likely climate changes are changes in the intensity and frequency of precipitation, more frequent heat waves, more persistent and extreme drought conditions and 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 may develop and deploy strategies for mitigating greenhouse gases and for adapting to unavoidable individual and collective impacts of climate change.

This report – the Synthesis and Assessment Product 4.6 (SAP 4.6) – focuses on impacts of global climate change, especially impacts 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.

ES.1 Survey of 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 can provide 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 supports the provision of many 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, wildfires, droughts, wind, hail, ice, heat, and cold.

Table ES.1 summarizes important climate change endpoints that are identified in the chapters for human health, human settlements, and human welfare, including anticipated impacts and adaptation strategies. The impacts should not be taken to be a comprehensive list of potential effects, but rather those that the available evidence suggests are likely to occur as a consequence of climatic changes. Not all effects have been equally well-studied. The effects identified for welfare, in particular, should be taken as examples of effects about which we have some knowledge, rather than a complete listing of all welfare effects.

Climate variability and change interact with existing and evolving 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 increasingly more distant 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 the convenience of air travel have made remote locations more accessible for work or recreation or retirement. These trends 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 the U.S. 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 (Table ES.2 summarizes regional vulnerabilities to a range of climate impacts).

ES.2 Summary of Effects of Climate Change on Human Health.

The United States is a highly developed country with a temperate climate. While there may be fewer cases of illness and death associated with climate change in the U.S. than in the developing world, we nevertheless anticipate substantial human health impacts. Greater wealth and a more developed public health infrastructure enhance our capacity to respond to climate change. Similarly, governments' capacities for disaster planning and emergency response are key assets that should allow the U.S. to adapt to many 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. According to the U.S. Census, 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. Similarly, heat-related mortality affects poor and minority populations disproportionately, in part due to lack of air conditioning. The concentration of poverty in inner city neighborhoods leads to disproportionate adverse effects associated with 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 densely populated 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, coastal evacuations prompted by imminent hurricane landfall are only moderately successful. Many of those who are advised to flee to higher ground stay behind in inadequate shelter. Surveys find that the public is either not aware of the appropriate preventive actions or incorrectly assesses the extent of their personal risk.

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, the impact of climate on food and water-borne pathogens will seldom be the only factor determining the burden of 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. Forest fires with their associated decrements to air quality and pulmonary effects 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.

ES.3 Summary of the Effects of Climate Change on Human Settlements

Effects of climate change on human settlements are likely to vary considerably according to location-specific vulnerabilities, with the most vulnerable areas likely to include: Alaska with increased permafrost melt, 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 the nation's 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. In the Pacific Northwest the electricity base dominated by hydropower is directly dependent upon the water flows from snowmelt. Reduced hydropower would mean the need for supplemental electricity sources, resulting in a wide variety of negative ripple effects to the economy and to human welfare. Similarly, along the West Coast, communities are likely to experience greater demands on water supplies even as regional precipitation declines and average snow packs decrease.

Communities in risk-prone regions have reason to be particularly concerned about potential increases in severe weather events. The combined effects of severe storms and sea-level rise in coastal areas or increased risks of fire in more arid areas are examples of how climate change may increase the magnitude of challenges already facing risk-prone regions. Vulnerabilities may be especially pronounced 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 adapt infrastructure and to 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 inflate business and household energy costs. Substantial equity effects will be entrained as energy needs increase, prices rise, and low income households are increasingly stressed and least able to adapt.

Climate change has the potential not only to affect communities directly but also through undermining their economic bases. Some regional economies are dependent on sectors that are highly sensitive to changes in climate, such as agriculture, forestry, water resources, or recreation and 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 be challenged, especially in locales with relatively limited social and political capital.

Finally, growth and development is generally moving toward those areas that are more likely to be vulnerable to the effects of climate change. 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 and zones with gradual land subsidence – will be at risk for sea level rise, especially related to severe storms and storm surges.

ES.4 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. There is a shared understanding that all three terms refer to aspects of individual and group life that improve living conditions and reduce chances of injury, stress, and loss.

Human well-being is typically defined and measured as a multi-dimensional concept. Taxonomies of place-specific well-being or quality of life 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 likely have impacts across all of these dimensions – both positive and negative. In addition, the positive and negative effects of climate change will affect broader communities, as networks of households, businesses, physical structures, and institutions are located together across space and time.

Quantifying impacts of climate change on human well-being 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. But most assessments of climate impacts have not focused on quantifying linkages from climate change to specific aspects of individual or collective welfare. 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 used by each sector (e.g., human illness and morbidity vs. reductions in numbers of species).

This report examines four types of effects on economic welfare: 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 goods 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 of climate change, 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. For instance, 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 temperature, however ambient conditions may eventually have adverse effects on outdoor activities like walking or beach recreation that is affected by sea level rise. Snow and ice sports are the most obvious loss among vulnerable recreation activities with the reduction in visitor use associated with a shorter season. But, decrements associated with snow-based recreation may be 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**.**

ES.5 Tables

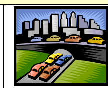
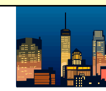
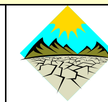
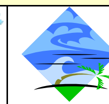
Table ES.1 Impacts of Climate Variability and Change on Human Health, Settlements, and Welfare in the United States (see likelihood discussion in Chapter 1)

Focus Area	Climate factor	Impact	Assessment *	Adaptation Strategies
HUMAN HEALTH				
	Extreme temperatures	Heat stress/stroke or hyperthermia	Very likely in Midwest and northeast urban centers	Early watch and warning systems and installation of cooling systems in residential and commercial buildings
	Changes 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 public transit, electric / hybrid vehicles, walking and bicycling to decrease emissions
	Air pollution degraded by wildfire	Asthma and COPD aggravated	Likely in California, the Intermountain	Public health air quality advisories

Focus Area	Climate factor	Impact	Assessment *	Adaptation Strategies
			West, the southwest and the southeast	
HUMAN SETTLEMENTS				
	Extreme temperatures	Increased net energy demand and expand capacity for peak cooling	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	Reallocate water among current users; develop water markets to encourage more efficient allocation; identify new sources through expansion of reservoirs; encourage conservation of water for personal and public use; develop drought resistant crops, resort to water pricing at replacement cost, work with states to develop property rights for water trading
	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, prescribed burns, thinning of combustible matter
	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;

Focus Area	Climate factor	Impact	Assessment *	Adaptation Strategies
				modify operation of existing infrastructure to account for changes in hydrology; develop drought resistant crops, water prices at replacement cost, enable trading by working with states to develop property rights
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; substantial economic disruption to recreation industry	Very likely in intermountain west, Northern New England and the Upper Great Lakes	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	Relocate dwellings and business, and reinforce structures and infrastructure to reduce disruptions

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

United States Census Regions	**Projected Percent Population Change 2000 to 2030**	**Record of Climate-Related Impacts by Census Region**								
										
		Early Snowmelt	Degraded Air Quality	Urban Heat Island	Wildfires	Heat Wave	Drought	Tropical Storms	Extreme Rainfall with Flooding	Sea Level Rise
New England ME VT NH MA RI CT	12.2	X	X	X		X	X		X	X
Middle Atlantic NY PA NJ	6.0	X	X	X		X	X	X	X	X
East North Central WI MI IL IN OH	7.7	X	X	X		X	X		X	
West North Central ND MN SD IA NE KS MO	13.6	X		X		X	X		X	
South Atlantic WV VA MD MC SC GA FL DC	50.8		X	X	X	X	X	X	X	X
East South Central KY TN MS AL	16.9					X	X	X		X
West South Central TX OK AR LA	44.0		X	X	X	X	X	X	X	X
Mountain MT ID WY NV UT CO AZ NM	64.6	X	X	X	X	X	X			
Pacific AK CA WA OR HI	38.2	X	X	X	X	X	X	X	X	X

Source: US.Census Bureau. State Interim Population Projections by Age and Sex: 2004 – 2030. www.census.gov/population/www/projections/projectionsagesex.html.

Synthesis and Assessment Product 4.6

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

Chapter 1: Introduction

Convening Lead Author: Janet L. Gamble, U.S. Environmental Protection Agency

Lead Authors: Kristie L. Ebi, ESS, LLC, Anne Grambsch, U.S. Environmental Protection Agency, Frances G. Sussman, Environmental Economics Consulting, Thomas J. Wilbanks, Oak Ridge National Laboratory

Contributing Authors: Colleen E. Reid, ASPH Fellow, Katharine Hayhoe, Texas Tech University, John V. Thomas, U.S. Environmental Protection Agency, Christopher P. Weaver, U.S. Environmental Protection Agency

Table of Contents

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 of the Potential Consequences of Climate Variability and Change on the United States. 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 the five strategic goals set forth 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: climate variability and change, evolving patterns of land use within the United States, and changes in the nation's population.

While the mandate for the preparation of this report calls for evaluating the impacts of global change, the emphasis is on those impacts associated with climate 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 change across three foci, including: human health, human settlements and human welfare. The three topics are fundamentally linked but unique dimensions of global change.

Human health is one of the most basic and direct measures of human welfare. Following past assessments of climate change impacts on human health, SAP 4.6 focuses on human morbidity and mortality associated with extreme weather, vector-, water- and foodborne diseases, and changes in air quality. Adaptation is a key component to evaluating human health vulnerabilities, including consideration of public health interventions (including prevention, response, and treatment strategies) that could be revised, supplemented, or implemented to protect human health and how much adaptation could be achieved.

Settlements are where people live. Humans live in a wide variety of settlements in the U.S., ranging from small villages and towns with a handful of people to metropolitan regions with millions of inhabitants. In particular, SAP 4.6 focuses on urban and highly-developed population centers in the U.S. Because of their high population density, urban areas multiply human health risks, and this is compounded by their relatively high proportions of the very old, the very young, and the poor. In addition, the components of infrastructure that support settlements, such as energy, water supply, transportation, and waste disposal, have varying degrees of vulnerability to climate change.

Welfare is an economic term used to describe the state of well-being of humans on an individual or collective basis. Human welfare is an elusive concept, and there is no single, commonly accepted definition or approach to thinking about welfare. There is, however, a shared understanding that increases in human welfare are associated with improvements in individual and communal conditions in areas such as political power, individual freedoms, economic power, social contacts, health 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. Some core aspects of quality of life are expressed directly in markets (e.g., income, consumption, personal wealth, etc.). The focus in SAP 4.6 is on non-market effects, although, these aspects of human welfare are often difficult to measure and value (Mendelsohn *et al.*, 1999; EPA, 2000).

The other Synthesis and Assessment Products related to CCSP's Goal 4 include reports on climate impacts on sea level rise (SAP 4.1), ecosystem changes (SAP 4.2), agricultural production (SAP 4.3), adaptive options for climate sensitive ecosystems (SAP 4.4), energy use (SAP 4.5) and transportation system impacts along the Gulf Coast (SAP 4.7). Collectively, these reports provide an overview of climate change impacts and adaptations related to a range of human conditions in the United States.

The audience for this report includes research scientists, public health practitioners, resource managers, urban planners, transportation planners, elected officials and other policy makers, and concerned citizens. A recent National Research Council analysis of global change assessments argues that the best assessments have an audience asking for them, and a broad range of stakeholders (U.S. National Research Council, 2007). This report clearly identifies the pertinent audience and what decisions it will inform.

Chapters 2-4 describe the impacts of climate change on human systems and outline opportunities for adaptation. SAP 4.6 addresses the questions of how and where climate change may impact U.S. socio-economic 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 to address a range of vulnerabilities. Risk assessments evaluate impacts of climate change across an array of characteristics, including: the magnitude of risk (both baseline and incremental risks), the distribution of risks across populations (including minimally-impacted individuals as compared to maximally-exposed individuals), and the availability, difficulty, irreversibility, and cost of adaptation strategies. While the state of science limits the ability to conduct formal, quantitative risk assessments, it is possible to develop information that is useful for formulating adaptation strategies. Primary goals for adaptation to climate variability and change include:

(i) To avoid maladaptive responses;
(ii) To establish protocols to detect and measure risks and to manage risks proactively when possible;
(iii) To leverage technical and institutional capacity;
(iv) To reduce current vulnerabilities to climate change;
(v) To develop adaptive capacity to address new climate risks that exceed conventional adaptive responses, and
(vi) To recognize and respond to impacts which play out across time. (Scheraga and Grambsch, 1998; WHO, 2003; IPCC, 2007b)

The issue of co-benefits is central in the consideration of adaptation to climate change. Many potential adaptive strategies have co-benefits. Along with helping human populations cope with climate change, adaptive strategies produce additional benefits. For example,

- Creating and implementing early warning systems and emergency response plans for heat waves can also improve those services for other emergency responses while improving all-hazards preparedness; (Glantz, 2004)
- Improving the infrastructure and capacity of combined sewer systems to avoid overflows due to changes in precipitation patterns also has the added benefit of decreasing contaminant flows that cause beach closings and impact the local ecology; (Rose *et al.*, 2001)
- A key adaptation technique for settlements in coastal zones is to promote maintenance or reconstruction of coastal wetlands ecosystems, which has the added benefit of creation or protection of coastal habitats (Rose *et al.*, 2001); and,
- Promotion of green building practices has added health and welfare benefits as improving natural light in office space and schools has been shown to increase productivity and mental health (Edwards and Torcellini, 2002).

Chapter 2 assesses the potential impacts of climate change on human health in the United States. Timely knowledge of human health impacts may support our public health infrastructure in devising and implementing strategies to prevent, compensate, or respond to these effects. For each of the health endpoints, the assessment addresses a number of topics, including:

- Reviewing evidence of the current burden associated with the identified health outcome;
- Characterizing the human health impacts of current climate variability and projected climate change (to the extent that the current literature allows);
- Discussing adaptation opportunities and support for effective decision making; and
- Outlining key knowledge gaps.

Each topic chapter 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. As such, the health chapter serves as an update to the Health Sector Assessment conducted as part of the First National Assessment in 2001.

Chapter 3 focuses on the climate change impacts and adaptations associated with human settlements in the United States. The IPCC Third and Fourth Assessment Reports (IPCC, 2001; IPCC, 2007c) conclude that settlements are among the human systems that are the most sensitive to climate change. For example, if there are changes in climate extremes there could be serious consequences for human settlements that are vulnerable to droughts and wildfires, coastal and river floods, sea level rise and storm surge, heat waves, land slides, and windstorms. However, specific changes in these conditions in specific places cannot yet be projected with great confidence. Chapter 3 focuses on the interactions between settlement characteristics, climate and other global stressors, with a particular focus on urban areas and other densely-developed population centers in the U.S.

The scale and complexity of these built environments, transportation networks, energy and resource demands, and the interdependence of these systems and their populaces, suggests that urban areas are especially vulnerable to multiplying impacts in response to externally imposed environmental stresses. The collective vulnerability of American urban centers may also be determined by the disproportionate share of urban growth in areas like the Inter-Mountain West or the Gulf Coast. The focus of Chapter 3 is on high density or rapidly-growing settlements and the potential for changes over time in the vulnerabilities associated with place-based characteristics (such as their climate regime, elevation, and proximity to coasts and rivers) and spatial characteristics (such as whether development patterns are sprawling or compact).

Chapter 4 focuses on the impacts of climate change on human welfare. To examine the impacts of climate change on human welfare, this chapter reports on two relevant bodies of literature: approaches to welfare that rely on both qualitative assessment and quantitative measures, and economic approaches that monetize, or place money values, on quantitative impacts.

Finally, Chapter 5 revisits the research recommendations and data gaps of previous assessment activities and describes the progress to date and the opportunities going forward. In addition, Chapter 5 reviews the overarching themes derived from Chapters 2-4.

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

(1) changes in climate in the United States;

(2) population trends, migration patterns, and the distribution of people across settlements;

(3) non-climate stressors and their interactions with climate change to realize complex impacts, and;

(4) a discussion of the handling of uncertainty in reporting scientific results.

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

In the following chapters, the authors examine the impacts on human society of global change, especially those associated with climate change. The impact assessments in Chapters 2-4 do not rely on specific emissions or climate change scenarios but, instead, rely on the state of the science with respect to our 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 merges our current understanding of climate change that has already occurred with changes that may occur. What is more, this assessment is not just related to changes that are projected to occur, but also projected changes in factors that are likely to affect sensitivity and vulnerability to climate. The report reviews historical trends along with current extreme events to point to vulnerabilities and then, where possible, determines the likely direction and range of potential climate-related impacts.

In the United States, we are observing the evidence of long-term changes in temperature and precipitation consistent with global warming. Changes in average conditions are being realized through rising temperatures, changes in annual and seasonal precipitation, and rising sea levels. Observations also indicate there are changes in extreme conditions, such as an increased frequency of heavy rainfall (with some increase in flooding), more heat waves, fewer very cold days, and an increase in areas affected by drought. Frequencies of tropical storms and hurricanes vary considerably from year to year and there are limitations in the quality of the data which make it difficult to discern trends, but evidence suggests some increases in their intensity and duration since the 1970s (Christensen *et al.*, 2007)

The brief overview that follows summarizes observed changes in the global climate as reported in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007a). 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. Note that the impacts described in the *Summary for Policy Makers* are based on global climate changes and may not pertain to all regions of the United States.

- "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 sea level."
- "Eleven of the last twelve years rank among the 12 warmest years in the instrumental record of global surface temperatures (since 1850)."
- "Average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming 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… Hot days, hot nights, and heat waves have become more frequent."
- "There is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970." (IPCC, 2007a)

In addition to the changes described in the IPCC *Summary for Policy Makers,* the following discussion examines U.S. climate trends and historical records related to temperature, precipitation, sea level rise, and changes in hurricanes and other catastrophic events. Information is also drawn from the North American Chapter of the IPCC Fourth Assessment Report and the Climate Change Science Programs Synthesis and Assessment Product 3.3: Weather and Climate Extremes in a Changing Climate. Taken together, this discussion provides a context from which to assess likely impacts of climate change on human health, human welfare, and human settlements.

1.2.1 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.*, 2007), temperatures across the continental U.S. have been rising at a rate of 0.1°F per decade since the early 1900s. Increases in average annual temperatures over the last century now exceed 1°F (Figure 1.1a). The degree of warming has varied by region across the United States, with the West and Alaska experiencing the greatest degree of warming (U.S. Environmental Protection Agency, 2007). These changes in temperature have led to an increase in the number of frost-free days, with the greatest increases occurring in the West and Southwest (Tebaldi *et al.*, 2006). The Intergovernmental Panel on Climate Change, in its most recent assessment report concluded that "Warming of the climate system is unequivocal…" (IPCC, 2007a).

Figure 1.1 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)

The current generation of global climate models, run with IPCC SRES scenarios of future greenhouse gas emissions, simulate future changes in the earth's climate system that are greater in magnitude and scope than those already observed. By the end of the 21st century, annual surface temperature increases are projected to range from 2-3°C near the coasts in the conterminous United States to more than 5°C in northern Alaska. Nationally, annual warming in the United States is projected to exceed 2^{o}C, with projected increases in summertime temperatures ranging between 3 and 5°C (greatest in the Southwest). The largest warming is projected to reach 10^{o}C for winter temperatures in the northernmost parts of Alaska. (Christensen *et al.*, 2007).

1.2.2 Trends in precipitation.

Shifting precipitation patterns have also been observed. Over the last century, annual precipitation across the continental U.S. has been increasing by an average of 0.18 inches per decade (Figure 1.1b). 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%. 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. The IPCC reports that rainfall is arriving in more intense events. (IPCC, 2007a).

El Niño events (a periodic warming of the tropical Pacific Ocean between South America and the International Date Line) are associated with increased precipitation and severe storms in some regions, such as the southeast U.S. and the Great Basin region of the western U.S. El Niño events have also been characterized by warmer temperatures and decreased precipitation in other areas, such as western Canada, the Pacific Northwest and parts of Alaska. Historically, El Niño events occur about every 3 to 7 years and alternate with the opposite phases of below-average temperatures in the eastern tropical Pacific (La Niña). Since 1976-1977, there has been a tendency toward more prolonged and stronger El Niños (IPCC, 2007a). However, recent analyses of climate simulations indicate no consistent trends in future El Niño amplitude or frequency (Meehl *et al.*, 2007)

Global model simulations summarized in the North American Chapter of the IPCC AR4, show moderate increases in precipitation (10% or less) over much of the United States over the next 100 years, except for the southwest. However, projected increases in these simulations are partially offset by increases in evaporation, resulting in greater drying in the central part of the United States. Projections for the central, eastern and western regions of the United States show similar seasonal characteristics (i.e., winter increases, summer decreases), although there is greater consensus for winter increases in the north and summer decreases in the south. However, uncertainty around the projected changes is large (Christensen *et al.*, 2007).

1.2.2.1 Changes in snow melt and glacial retreat.

Warmer temperatures are melting mountain glaciers and 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 one day per decade for streams in the Northeast (Huntington *et al.*, 2003).

This trend is projected to continue, with more precipitation falling as rain rather than snow, and snow season length and snow depth are generally projected to decrease in most of the country. Such changes tend to favor increased risk of winter flooding and lower summer soil moisture and streamflows (Christensen *et al.*, 2007).

1.2.3 Rising sea levels and erosion of coastal zones

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; IPCC, 2007a). 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). In the past century, global sea level rose 5-8 inches.

Rising global temperatures are projected to accelerate the rate of sea-level rise by further expanding ocean water, melting mountain glaciers, and increasing the rate at which Greenland and Antarctic ice sheets melt or discharge ice into the oceans. Estimates of sea-level rise for a global temperature increase between 1.1 and 6.4^{o}C (the IPCC estimate of likely temperature increases by 2100) are about 7 to 23 inches (0.18m to 0.59m), excluding the contribution from accelerated ice discharges from the Greenland and Antarctica ice sheets. Extrapolating the recent acceleration of ice discharges from the polar ice sheets would imply an additional contribution up to 8 inches (20cm). If melting of these ice caps increases, larger values of sea-level rise cannot be excluded (IPCC, 2007a).

For additional details about sea level rise and its effects on US coasts please see Synthesis and Assessment Product 4.1 *Coastal elevations and sensitivity to sea level rise*

1.2.4 Changes in Extreme Conditions

The climatic changes described above are often referred to as changes in "average" conditions. Most observations of temperature will tend to be close to the average: days with very hot temperatures happen infrequently. Similarly, only rarely will there be days with extremely heavy precipitation. Climate change could result in a shift of the entire distribution of a meteorological variable so that a relatively small shift in the mean could be accompanied by a relatively large change in the number of relatively rare (according to today's perspective) events. For example, with an increase in average temperatures, it would be expected there would be an increase in the number of very hot days and a decrease in the number of very cold days. Other, relatively rare, extreme events of concern for human health, welfare and settlements include hurricanes, floods and droughts.

In general, it is difficult to attribute any individual extreme event to a changing climate. Because extreme events occur infrequently, there is typically limited information to characterize these events and their trends. In addition, extreme events usually require several conditions to exist for the event to occur, so that linking a particular extreme event to a single, specific cause is problematic. For some extreme events, such as extremely hot/cold days or rainfall extremes, there is more of an observational basis for analyzing trends, increasing our understanding and ability to project future changes.

Finally, there are many different aspects to extremes. Frequency is perhaps the most often discussed but changes in other aspects of extremes such as intensity (e.g., warmer hot days), time of occurrence (e.g., earlier snowmelt), duration (e.g., longer droughts), spatial extent and location are also important when determining impacts on human systems.

Synthesis and Assessment Product 3.3 *Weather and Climate Extremes in a Changing Climate* (CCSP, 2008) has a much more detailed discussion of climate extremes that are only very briefly described here. The interested reader is referred to that report for additional details.

1.2.4.1 Heat and cold waves

Extreme temperatures (e.g., temperatures in the upper 90th or 95th percentile of the distribution) often change in parallel with average temperatures. Since 1950, there are more 3-day warm spells (exceeding the 90th percentile) when averaged over all of North America (Peterson *et al* , 2008). While the number of heat waves has increased, the heat waves of the 1930s remain the most severe in the U.S. historical record. Mirroring this shift toward more hot days is a decrease in unusually cold days during the last few decades. There has been a corresponding decrease in frost days and a lengthening of the frost-free season over the past century. The number of frost days decreased by four days per year in the United States during the 1948-1999 period, with the largest decreases, as many as 13 days per year, occurring in the western United States (Easterling, 2002). For the United States, the average length of the frost-free season over the 20th century increased by almost two weeks (Kunkel *et al.*, 2004).

Recent studies have found that there is an increased likelihood of more intense, longer-lasting and more frequent heat waves (Meehl and Tebaldi, 2004, Schar *et al.*, 2004, Clark *et al.*, 2006). As the climate warms, the number of frost days is expected to decrease (Cubasch *et al.*, 2001) particularly along the northwest coast of North America (Meehl *et al.*, 2004). SAP 4.6, using a range of greenhouse gas emission scenarios and model simulations, found that hot days, hot nights and heat waves are very likely to become more frequent, that cold days and cold nights are very likely to become much less frequent, and that the number of days with frost is very likely to decrease (CCSP, 2008). Growing season length is related to frost days, which is projected to increase in a warmer climate in most areas (Tebaldi *et al.*, 2006).

1.2.4.2 Heavy Precipitation Events.

Over the 20th century, periods of heavy downpours became more frequent and more intense and accounted for a larger percentage of total precipitation (Karl and Knight, 1997; Groisman *et al.*, 1999, 2001, 2004, 2005; Kunkel *et al.*, 1999; Easterling *et al.*, 2000; Kunkel, 2003). These heavy rainfall events have increased in frequency by as much as 100% across much of the Midwest and Northeast over the last century (Kunkel *et al.*, 1999). These findings are consistent with observed warming and associated increases in atmospheric water vapor.

The intensity of precipitation events is projected to increase, particularly in high latitude areas that experience increases in mean precipitation (Meehl *et al.*, 2007). In areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. Precipitation extremes increase more than does the mean in most tropical and mid- and high-latitude areas. Some studies project widespread increases in extreme precipitation (Christensen *et al.*, 2007), with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation. SAP 3.3 concluded that, over most regions, future precipitation is likely to be less frequent but more intense, and precipitation extremes are very likely to increase (CCSP 2008).

1.2.4.3 Changes in Flooding.

Heavy rainfall clearly can lead to flooding, but assessing whether observed changes in precipitation have lead to similar trends in flooding is difficult for a number of reasons. In particular, there are many human influences on streamflow (e.g., dams, land-use changes, etc.) that confound climatic influences. In some cases, researchers using the same data came to opposite assessments about trends in high streamflows (Lins and Slack, 1999, 2005; Groisman *et al.*, 2001, 2004). Short duration extreme precipitation events can lead to localized flash flooding, but for large river basins, significant flooding will not occur from these types of episodes alone; excessive precipitation must be sustained for weeks to months for flooding to occur.

1.2.4.4 Changes in droughts

An extended period with little precipitation is the main cause of drought, but the intensity of a drought can be exacerbated by high temperatures and winds, a lack of cloudiness/low humidity which result in high evaporation rates. Droughts occur on a range of geographic scales and can vary in their duration, in some cases lasting years. The 1930s and the 1950s experienced the most widespread and severe drought conditions (Andreadis *et al.*, 2005), although the early 2000s also saw severe droughts in some areas, especially in the western United States (Piechota *et al.*, 2004).

Based on observations averaged over the United States, there is no clear overall national trend in droughts (CCSP, 2008). Over the past century, the area affected by severe and extreme drought in the United States each year averaged about 14%: by comparison, in 1934 the area affected by drought was as high as 65% (CCSP, 2008). In recent years, the drought-affected area ranged between 35 and 40% (CCSP, 2008). These trends at the national level however mask important differences in drought conditions at regional scales: one area may be very dry while another is wet. For example, in the Southwest and parts of the interior of the West increased temperatures have led to rising drought trends (Groisman *et al.*, 2004; Andreadis and Lettenmaier, 2006). In the Southwest, the 1950s were the driest period, though droughts in the past 10 years are approaching the 1950s drought (CCSP, 2008). There are also recent regional tendencies toward more severe droughts in parts of Alaska (CCSP, 2008).

Several generations of global climate models, including the most recent find an increase in summer drying in the mid latitudes in a future, warmer climate (Meehl *et al.*, 2007). This tendency for drying of the mid-continental areas during summer indicates a greater risk of droughts in those regions (CCSP, 2008). Analyses using several coupled global circulation models project an increased frequency of droughts lasting a month or longer in the Northeast (Hayhoe *et al.*, 2007) and greatly reduced annual water availability over the Southwest (Milly *et al.*, 2005). SAP 3.3 concluded that droughts are likely to become more frequent and severe in some regions of the country as higher air temperatures increase the potential for evaporation.

1.2.4.5 Changes in hurricanes

Assessing changes in hurricanes is difficult: There have been large fluctuations in the number of hurricanes from year to year and from decade to decade. Furthermore, it is only since the 1960s that reliable data can be assembled for assessing trends. In general, there is increasing uncertainty in the data record the further back in time one goes. For example, prior to satellites, hurricanes that remained out at sea or that struck sparsely inhabited areas could be missed entirely: it has been estimated that about three tropical cyclones per year are missing in the pre-satellite data (Landsea and Knabb, 2007). Even taking these factors into account, SAP 3.3 concluded that it is likely that the annual numbers of tropical storms, hurricanes, and major hurricanes in the North Atlantic have increased over the past 100 years. However, the existing data and an adjusted record of tropical storms indicate no significant linear trends beginning from the mid- to late 1800s to 2005 (CCSP, 2008). Moreover, SAP 3.3 concluded that there is no evidence for a long-term increase in North American mainland land-falling hurricanes.

Evidence suggests that the intensity of Atlantic hurricanes and tropical storms has increased over the past 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; CCSP, 2007a). An increase in extreme wave heights in the Atlantic since the 1970s has been observed: consistent with more frequent and intense hurricanes (CCSP, 2008).

For North Atlantic hurricanes, it is likely that wind speeds and core rainfall rates will increase (Henderson-Sellers *et al.*, 1998; Knutson and Tuleya, 2004, 2008; Emanuel, 2005). However, the CCSP concluded that “frequency changes are currently too uncertain for confident projection” (CCSP, 2008). The CCSP also found that the spatial distribution of hurricanes will likely change (CCSP, 2008). Storm surge is likely to increase due to projected sea level rise (CCSP, 2008).

1.3 Population Trends and Migration Patterns: A Context for Assessing Climate-related Impacts

Assessments of climate-related risk must account for the size of the population, including especially sensitive sub-populations, and their geographic distribution across the landscape. The following discussion provides a basis for assessing the interactions of global change within the larger context of demographic trends. In particular, the social characteristics of a populace may interact with its spatial distribution to produce a non-linear risk. In such instances, risk assessments are shaped by questions such as:

- *Which counties, states, and regions will grow most rapidly?*
- *How many people will live in at-risk areas, such as coastal zones, flood plains, and arid areas?*
- *What share of retirees will migrate and where will they move?*

1.3.1 Trends in total U.S. Population

The US population numbered some 280 million individuals in 2000.[1] In 1900, the US population numbered about 76 million people; fifty years later the population had roughly doubled to 151 million people.

Population projections are estimates of the population at future dates. They are based on assumptions about future births, deaths, international migration, and domestic migration and represent plausible scenarios of future population.

In 2000 the IPCC published a set of emission scenarios for use in the Third Assessment Report (Nakicenovic *et al*., 2000). The SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The SRES team defined four narrative storylines labeled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways. (Nakicenovic *et al*., 2000)

The US Census Bureau periodically releases projections for the resident population of the United States based on Census data. The cohort-component methodology[2] is used in these projections. Alternative assumptions of fertility, life expectancy, and net immigration yield low, middle and high projections.

Figure 1.2 displays the SRES and Census population projections[3] for the US. The Census projections span a greater range than the SRES scenarios: by 2100 the low series projection of 282 million is below the current population while the high projection is about 1.2 billion, or about four times the current population. The Census middle series projection is relatively close to the SRES A2 scenario (570 million vs. 628 million in 2100), while the SRES A1/B1 and B2 scenarios fall below the Census middle projection.

---

[1] Information on historical US population data and current population estimates and projections can be found at http://www.census.gov/.
[2] See Census web-site for additional details on the projection methodology.
[3] The Census projections are based on the 1990 Census. Preliminary projections based on the 2000 Census for 2000-2050 are available.

Figure 1.2 US Population Projections 2000-2100.

1.3.1.1 Aging of the population

The US population has not simply increased by 300% over the past century, it has also shifted in its demographic structure. For example, in 1900 less than 4% of the US population was 65 years or older; currently about 12% of Americans are 65 or older (He *et al.*, 2005). By 2050, the US population aged 65 and older is projected to be about 86 million, or about 21% of the total population. Nearly 5% of the projected population in 2050, over 20 million people, will be 85 years or older (He *et al.*, 2005). Figure 1.3 displays the projected age distribution for the total resident population of the United States by sex for the middle projection series.

Figure 1.3 Population Pyramids of the US 2000 and 2050 (Interim Projections based on 2000 Census)

The projected increase in the elderly population is an important variable in projections of the effects of climate change. The elderly are identified in many health assessments as more vulnerable than younger age groups to a range of health outcomes associated with climate change, including injury resulting from weather extremes such as heatwaves, storms and floods (WHO, 2003; IPCC 2007b; NAST, 2001). Aging also can be expected to be accompanied by multiple, chronic illnesses that may result in increased vulnerability to infectious disease (NAST, 2001). Chapter two in this report also identifies the elderly as a vulnerable subpopulation.

1.3.2 Migration patterns

Although numbers produced by population projections are important, the striking relationship between potential future settlement patterns and the areas that may experience significant impacts of climate change is the critical insight. In particular, nearly all trends point to more Americans living in areas that may be especially vulnerable to the effects of climate change (see Figure 1.4). For example, many rapidly growing places in the Mountain West may also experience decreased snow pack during winter and earlier spring melting, leading to lower stream flows, particularly during the high-demand period of summer.

The continued growth of arid states in the West is therefore a critical crossroads for human settlements and climate change. These states are expected to account for one-third of all U.S. population growth over the next 25 years (US Census Bureau, 2005). The combined effects of growing demand for water due to a growing population and changes in water supplies associated with climatic change pose important challenges for these states. 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, 2007).

Figure 1.4: 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).

Growth in coastal population has kept pace with population growth in other parts of the country, but given the small land area of the coasts, the density of coastal communities has been increasing (Crossett *et al.*, 2004). Over 50% of the US population now lives in the coastal zone, and coastal areas are projected to continue to increase in population, with associated increases in population density, over the next several decades. The overlay of this migration pattern with climate change projections has several implications. Perhaps the most obvious is the increased exposure of people and property to the effects of sea level rise and hurricanes (Kunkel *et al.*, 1999). With rapidly growing communities near coastlines, property damages would be expected to increase even without any changes in storm frequency or intensity (Changnon *et al.*, 2003).

1.3.2.1 How Climate Impacts Migration Patterns

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.[4] 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 different regions.

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 vary[5] the conclusions are similar. In general:

- People move for a variety of reasons other than climate, such as: proximity to family and friends, employment opportunities, lower cost of living, and aesthetics,
- 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). In addition, new information technologies may make it possible for some urban dwellers to move to and work from rural regions.

[4] http://www.census.gov/Press-Release/www/2002/sumfile3.html
[5] Study methodologies include: aggregate studies of population changes alongside regional characteristics, explanatory models developed from individual migration data and individual surveys.

1.4. Complex Linkages: The Role of Non-climate Factors

Climate is only one of a number of global changes that affect human well-being. These non-climate processes and stresses interact with climate change, determining the overall severity of climate impacts. Moreover, climate change impacts can spread from directly impacted areas and sectors to other areas and sectors through extensive and complex linkages (IPCC, 2007b). Evaluating future climate change impacts therefore require assumptions, explicit and implicit, about how future socioeconomic conditions will develop. The IPCC (1994) recommends the use of socioeconomic scenarios in impacts assessments to capture in a consistent way these factors.

Socioeconomic scenarios have tended to focus on variables such as population and measures of economic activity (e.g., Gross Domestic Product) that can be quantified using well-established models or methods (for examples of economic models which have been used for long run projections, see Nakicenovic *et al.*, 2000; NAST 2001; Yohe *et al.*, 2007). While useful as a starting point, some key socioeconomic factors may not allow this type of quantification: they could however be incorporated through a qualitative, "storyline" approach and thus yield a more fully developed socioeconomic scenario. The UNEP country study program guidance (Tol, 1998) notes the role of formal modeling in filling in (but not defining) socioeconomic scenarios but also emphasizes the role of expert judgment in blending disparate elements into coherent and plausible scenarios. Generally socioeconomic scenarios have been developed in situations where it is not possible to assign levels of probability to any particular future state of the world and therefore it usually is not appropriate to make confidence statements with respect to a specific socioeconomic scenario (Moss and Schneider, 2000).

Socioeconomic scenarios include non-environmental factors that influence exposures, vulnerability and impacts. Factors that may be incorporated into a scenario include:

- population (e.g., demographics, migration patterns),
- economic status (income, prices)
- technology (e.g., pesticides, vaccines, transportation modes, wireless communications)
- infrastructure (e.g., water treatment plants, sewers, and drinking water systems; public health systems; roads, rails and bridges; flood control structures)
- human capital and social context and behaviors (e.g., skills and knowledge, social networks, lifestyles, diet), and
- institutions (legislative, social, managerial).

These factors are important both for characterizing potential effects of a changing climate on human health, settlements and welfare and for evaluating the ability of the US to adapt to climate change.

1.4.1 Economic status

The US is a developed economy with GDP approaching $14 trillion and per capita income of $38,611 in 2007 (US BEA, 2008). The US economy has large private and public sectors, with strong emphasis on market mechanisms and private ownership (Christensen *et al.*, 2007). A nation's economic status clearly is important for determining vulnerability to climate change: wealthy nations have the economic resources to invest in adaptive measures and bear the costs of impacts and adaptation thereby reducing their vulnerability (WHO, 2003, IPCC, 2001). With the aging of the population (described in Section 1.3.1.1) however, the costs of health care are likely to rise over the coming decades (Christensen *et al.*, 2007). Moreover, if the trend toward globalization continues through the 21st century, markets, primary factors of production, ownership of assets, and policies and governance will become more international in outlook (Stiglitz, 2002). Unfortunately, there has been little research to understand how these economic trends interact with climate change to affect vulnerability (i.e., whether they facilitate or hinder adaptation to climate change in the US).

1.4.2 Technology

The past half-century has seen stunning levels of technological advancement in the U.S. which has done much to improve American standards of living. The availability and access to technology at varying levels, in key sectors such as energy, agriculture, water, transportation and health is a key component to understanding vulnerability to climate change. Many technological changes, both large and small, have reduced American's vulnerability to climate change (NAST, 2001). Improved roads and automobiles, better weather and climate forecasting systems, computers and wireless communication, new drugs and vaccines, better building materials, more efficient energy production – the list is very long indeed– have contributed to America's material well being while reducing vulnerability to climate. Many of the adaptive strategies that are currently deployed that protect human beings from climate involve technology (e.g., warning systems, air conditioning and heating, pollution controls, building design, storm shelters, vector control, water treatment and sanitation) (WHO, 2003). Continued advances in technology in the 21st century can increase substantially our ability to cope with climate change (IPCC, 2007a; USGCRP, 2001).

However, it will be important to assess risks from proposed technological adaptations to avoid or mitigate adverse effects (i.e., maladaptation) (Patz, 1996; Klein and Tol, 1997). For example, if new pesticides are used to control disease vectors their effects on human populations, insect predators, and insect resistance to pesticides need to be considered (Scheraga and Grambsch, 1998; Gubler *et al.*, 2001).

In addition, technological change can interact in complex ways with other socioeconomic factors (e.g., migration patterns) and affect vulnerability to climate change. For example, 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). More recently, the rapid development of new information technologies, such as the internet, have made previously remote locations more accessible for work, recreation, or retirement. Whether these developments increase or decrease vulnerability is unknown, but they do indicate the need for socioeconomic scenarios to better characterize the complex linkages between climate and non-climate factors in order evaluate vulnerability.

1.4.3 Infrastructure

Communities have reduced, and can further reduce, their vulnerability to adverse climate effects through investments in infrastructure. For example, water resources in the US have been modified and intensively managed over the years, partly in response to climate variability (Cohan and Miller, 2001). These investments range from small, privately constructed impoundments, water diversions and levees to major projects constructed by federal and state governments. Public health infrastructures, such as sanitation facilities, waste water treatment, and laboratory buildings reduce climate change health risks (Grambsch and Menne, 2003). Coastal communities have developed an array of systems to manage erosion and protect against flooding (see SAP 4.1 for an extensive discussion). More generally infrastructure such as roads, rails and bridges, water supply systems and drainage, mass transit and buildings can reduce vulnerability (Grambsch and Menne, 2003).

However, infrastructure can increase vulnerability if its presence encourages people to locate in more vulnerable areas. For example, increasing the density of people in coastal metropolitan areas, dependent on extensive fixed infrastructure, can increase vulnerability to extreme events such as floods, storm surges and heat waves (NAST, 2001). In assessments of severe storms, measures of property damage are consistently higher and loss of life lower in the US when compared with less-developed countries (Cohan and Miller, 2001), reflecting both the high level of development in coastal zones and the effectiveness of warnings and emergency preparedness (Piekle and Pielke, 1997).

Fixed infrastructure itself has the potential to be adversely impacted by climate change, which can increase vulnerability to climate change. For example, flooding can overwhelm sanitation infrastructure and lead to water-related illnesses (Grambsch and Menne, 2003). Much of the transportation infrastructure in the Gulf Coast has been constructed on land at elevations below 16.4 ft: storm surge, therefore poses risks of immediate flooding of infrastructure and damage caused by the force of floodwaters (see SAP 4.7 for additional information on the vulnerability of Gulf Coast transportation infrastructure to climate change). Damage to transportation infrastructure can make it more difficult to assist affected populations (Grambsch and Menne, 2003).

1.4.4 Human and Social Capital and Behaviors

While these factors are extremely difficult to quantify, much less project into the future, they are widely perceived to be important in determining vulnerability in a number of different ways. In general, countries with higher levels of “human capital” or knowledge are considered to be less vulnerable to climate change. Effective adaptation will require individuals skilled at recognizing, reporting and responding to climate change effects. Moreover, a number of the adaptive measures described in the literature require knowledgeable, trained and skilled personnel to implement them. For example, skilled public health managers, who understand surveillance and diagnostic information, will be needed to mobilize appropriate responses. People trained in the operation, quality control and maintenance of laboratories, communications equipment, and sanitation, wastewater, and water supply systems are also key (Grambsch and Menne, 2003). Researchers and scientists spanning a broad range of disciplines will be needed to provide a sound basis for adaptive responses.

In addition to a countries’ human capital (i.e., the knowledge, experience and expertise of its citizens) the relationships, exchange of resources and knowledge, and the levels of trust and conflicts between individuals (i.e., “social capital”) are also important for understanding future vulnerability to climate change (Adger 2003; Lehtonen 2004; Pelling and High 2005). Social networks can play an important role in coping and recovery from extreme weather events (Adger, 2003). For example, individuals who were socially isolated were found to be a greater risk of dying from extreme heat (Semenza *et al.*, 1996), as well as people living in neighborhoods without public gathering places and active street life (Klinenberg 2002).

Individual behaviors and responses to changing conditions also determine vulnerability. For example, fitness, body composition, and level of activity are among the factors that determine the impact extremely hot weather will have on the human body (see Chapter 2 for additional information). Over the past three decades, there has been a dramatic increase in obesity and associated health conditions such as diabetes[6] (Flegal *et al.*, 1998.). Whether this trend continues or not could have important implications for determining vulnerability to climate change. Individual responses and actions to reduce their exposures to extreme heat can also substantially ameliorate adverse health impacts (McGeehin and Mirabelli, 2001). Successfully motivating individuals to respond appropriately can therefore decrease vulnerability and reduce health impacts -- a key goal of public health efforts (McGeehin and Mirabelli, 2001).

1.4.5 Institutions

The ability to respond to climate change and reduce vulnerability is influenced by social institutions as well as the social factors noted above. Institutions are viewed broadly in the climate change context and include a wide diversity of things such as regulations, rules and norms that guide behavior. Examples include past development and land use patterns, existing environmental and coastal laws; building codes, and legal rights. Institutions also can determine a decision-maker's access to information and the ways in which the information can be used (Moser *et al.*, 2007).

Well-functioning institutions are essential to a modern society and provide a mechanism for stability in otherwise volatile environments (Moser *et al.*, 2007). Future options for responding to future climate impacts are thus shaped by our past and present institutions and how they evolve over time. In addition, the complex interaction of issues expected with climate change may require new arrangements and collaborations between institutions to address risks effectively, thereby enhancing adaptive capacity (Grambsch and Menne, 2003). A number of institutional changes have been identified that improve adaptive capacity and reduce vulnerability (see Chapter 3 for additional details). While the importance of institutions is clear, there are few scenarios which incorporate an explicit representation of them.

1.4.6 Interacting effects

The same social and economic systems that bear the stress of climate change also bear the stress of non-climate factors, including: air and water pollution, the influx of immigrants, and an aging 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 emergency preparedness.

[6] See http://www.cdc.gov/nccdphp/dnpa/obesity/ for additional data and information.

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 lives and 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 the resulting tangle of climate and non-climate stressors that complicate efforts to respond and to adapt. Certainly, the impacts following these hurricanes reveal that socioeconomic factors and failures in human systems may be as damaging as the storms themselves.

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 living in poverty in America's suburbs. Many of these people 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 study: "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).

1.5 Reporting Uncertainty in SAP 4.6

Uncertainty can be traced to a variety of sources: (1) a misspecification of the cause(s), such as the omission of a causal factor resulting in spurious correlations; (2) mischaracterization of the effect(s), such as a model that predicts cooling rather than warming; (3) absence of or imprecise measurement or calibration (such as devices that fail to detect minute causal agents); (4) fundamental stochastic (chance) processes; (5) ambiguity over the temporal ordering of cause and effect; (6) time delays in cause and effect; and, (7) complexity where cause and effect between certain factors are camouflaged by a context with multiple causes and effects, feedback loops, and considerable noise.

A new perspective on the treatment of uncertainty has emerged from the IPCC Third and Fourth Assessment processes. This new perspective suggests that uncertainties about projections of climate changes, impacts, and responses include two fundamentally different dimensions. One dimension recognizes that most processes and systems being observed are characterized by inherent variability in outcomes, the more variable the process or system, the greater the uncertainty associated with any attempt to project an outcome. A second dimension recognizes limitations in our knowledge about processes and systems. These two dimensions are different in what they imply about the value of research for improving the treatment of uncertainty. Research can certainly reduce uncertainties associated with knowledge limitations, which can sharpen a focus on more likely outcomes.

This report is a summary of the state of the science on the impacts of climate change on human health, human settlements and human welfare. With this focus, the assessment of uncertainty in this report is based on a comprehensive reading of the literature and the author's expert judgment, in which authors assign a confidence level to the major statements on the basis of an assessment of current knowledge. The considerations in determining confidence should include 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. This can be thought of using two different dimensions related to consensus, as shown in Figure 1.5.

Figure 1.5 Considerations in determining confidence.

In this report, each chapter author team comprehensively read the literature and assigned likelihood judgments that reflect their assessment, based on the current consensus in the science, the quality and amount of evidence as well as their expert judgment, that the given climate impact statement is likely to be true. The likelihood terminology and their corresponding values that are used in this report are shown in Table 1.2. As the focus of this report is on impacts, it is important to note that these likelihood statements refer to the statement of the impact, not statements related to underlying climatic changes.

The application of this approach to likelihood estimates demonstrates some variability across each of the three core chapters (Chapters 2-4). This variability in reporting uncertainty is based on the richness of their respective knowledge bases. A relatively more extensive and specific application of likelihood and state of the knowledge estimates 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.

1.6 References

AARP (2006) Aging, Migration, and Local Communities: The Views of 60+ Residents and Community Leaders. Published September 2006

Adger, W. N. (2003) Social capital, collective action and adaptation to climate change. Economic Geography 79(4), 387-404.

Andreadis KM, Clark EA, Wood AW, Hamlet AF, and Lettenmaier DP. 2005. 20th century drought in the conterminous United States. J. Hydrometeor., 6(6): 985-1001.

Andreadis KM, and DP Lettenmaier. 2006. Trends in 20th century drought over the continental United States. Geophysical Research Letters, 33, doi:10.1029/2006GL025711.

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

Bernard SM, JM Samet, A Grambsch, KL Ebi, I Romieu. May 2001. The Potential Impacts of Climate Variability and Change on Air Pollution-Related Health Effects in the United States. Environmental Health Perspectives. 109 (Supplement 2): 199-209.

Bernard, Susan M. and Michael A. McGeehin (2004) Municipal Heat Wave Response Plans September 2004, 94(9) American Journal of Public Health pp. 1520-1522.

Berube, Alan and Elizabeth Kneebone (2006) *Two Steps Back: City and Suburban Poverty Trends 1999–2005*. Brookings Metropolitan Policy Program.

Borrell, Carme, Marc Marí-Dell'Olmo, Maica Rodríguez-Sanz, Patrícia Garcia-Olalla, Joan A. Caylà, Joan Benach and Carles Muntaner (2006) Socioeconomic position and excess mortality during the heat wave of 2003 in Barcelona. Journal European Journal of Epidemiology. 21(9) September, 2006. pp. 633-640.

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

Carruthers, John I., Alexander C. Vias (2005) Urban, Suburban, and Exurban Sprawl in the Rocky Mountain West: Evidence from Regional Adjustment Models Journal of Regional Science 45 (1), 21–48.

Cayan, Dan, Amy Lynd Luers, Michael Hanemann, Guido Franco and Bart Croes (2006) Scenarios of Climate Change in California: An Overview. A Report From: California Climate Change Center.

CCSP. 2003. Strategic Plan for the U.S. Climate Change Science Program. Climate Change Science Program and the Subcommittee on Global Change Research.

CCSP, 2008: *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Thomas R. Karl, Gerald A. Meehl, Christopher D. Miller, Susan J. Hassol, Anne M. Waple, and William L. Murray (eds.)]. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., USA, 164 pp.

Centers for Disease Control and Prevention: Morbidity and Mortality Weekly Report. Heat-Related Deaths—Los Angeles County, California, 1999-2000, and United States, 1979-1998

Chagnon, S. 2003. Shifting Economic Impacts from Weather Extremes in the United States: Result of Societal Changes, Not Global Warming. *Natural Hazards* 29, 273-290.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark R, Brown S, and Murphy J. 2006. Modelling norther hemisphere summer heat extreme changes and their uncertainties using a physics ensemble of climate sensitivity experiments. Journal of Climate 19(17): 4418-4435.

Cohan and Miller 2001

Cromartie John B. (1998) Net Migration in the Great Plains Increasingly Linked to Natural Amenities and Suburbanization. Rural Development Perspectives. 13 (1). pp. 27-34.

Crossett KM, TJ Culliton, PC Wiley, TR Goodspeed. 2004. Population Trends Along the Coastal United States: 1980-2008. National Oceanographic and Atmospheric Administration, Washington, DC.

Cubasch U., Meehl G.A., Boer G.J., Stouffer R.J., Dix M., Noda A., Senior C.A. Raper S., Yap K.S. 2001. Projections of future climate. In" Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T. and the Core Writing Team (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Easterling, D.R., Karl, T.R., Lawrimore, J.H. and Del Greco, S.A. 1999. *United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data for 1871-1997*. ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., and Mearns, L.O. 2000. Climate extremes: Observations, modeling, and impacts. *Science* 289, 2068–2074.

Easterling, D.R. 2002. Recent Changes in Frost Days and the Frost-Free Season in the United States. Bulletin of the American Meteorological Society, 83(9):1327-1332.

Edwards L. and P. Torcellini. 2002. A Literature Review of the Effects of Natural Light on Building Occupants. Natural Renewable Energy Laboratory Technical Report. TP-550-30769.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436, 686-688.

EPA, 2000. Guidelines for Preparing Economic Analyses. EPA 240-R-00-003.

Field CB, LD Mortsch, M Brklacich, DL Forbes, P. Kovacs, JA Patz, SW Running and MJ Scott. 2007. North America. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. ML Parry, *et al.*, Eds, Cambridge University Press, Cambridge, UK, 617-652.

Flegal, K.M., Carroll, M.D.; Kuczmarski, R.J.; *et al.* Overweight and obesity in the United States: Prevalence and trends, 1960–1994. *International Journal of Obesity* 22(1):39-47, 1998.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Tank, A. and Peterson, T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* 19, 193–212.

Garreau, Joel (1991) Edge Cities: Life on the New Frontier. Anchor Press.

Glantz, Michael H. (2004) Early Warning Systems: Do's and Don'ts. Report of Workshop, Shanghai, China. National Center for Atmospheric Research.

Graham, Stephen and Simon Marvin (1996) Telecommunications and the City: Electronic Spaces, Urban Places. London. Routledge Press.

Grambsch A.. and B. Menne. 2003. "Adaptation and adaptive capacity in the public health context" in Climate Change and Human Health: Risks and Responses (Eds. A.J. McMichael et. al), WHO, WMO, UNEP.

Greenough G, M McGeehin, SM Bernard, J Trtanj, J Riad, D Engelberg. May 2001. The Potential Impacts of Climate Variability and Change on Health Impacts of Extreme Weather Events in the United States. Environmental Health Perspectives. 109 (Supplement 2): 191-198.

Groisman PY, Karl TR, Easterling DR, Knight RW, Jamason PB, Hennessy KJ, et al. Changes in the probability of heavy precipitation:
important indicators of climatic change. Clim Change 1999;42: 243–83.

Groisman PY, Knight RW, Karl TR. Heavy precipitation and high streamflow in the United States: trends in the 20th century. Bull Am Meteorol Soc 2001;82:219– 46.

Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, Razuvaez VN. 2004. Trends in Precipitation Intensity In The Climate Record. American Geophysical Union, Spring Meeting 2004, abstract #A52A-06.

Groisman PY, Knight RW, Easterling DR, Levinson D, Heim RR, Karl TR, Whitfield PH, Hegerl GC, Razuvaez BG, Sherstyukov JG, Enloe JG, and Stroumentova NS. 2005. Changes in precipitation distribution spectra and contemporary warming of the extratropics: implications for intense rainfall, droughts, and potential forest fire danger. 16th Conference on Climate Variability and Change, January 2005.

Gubler DJ, P Reiter, KL Ebi, W Yap, R Nasci, JA Patz. May 2001. Climate Variability and Change in the United States: Potential Impacts on Vector- and Rodent-Borne Diseases. Environmental Health Perspectives. 109 (Supplement 2): 223-233.

Hall, M.H.P. and Fagre, D.B. 2003 Modeled climate-induced glacier change in Glacier National Park, 1850-2100. *Bioscience* 53, 131-140.

Hanson, Susan and Genevieve Giuliano (eds). (2004). The Geography of Urban Transportation, 3rd Edition. New York: Guilford Press.

Hayhoe K, Wake CP, Huntington TG, Lifeng L, Schwartz MD, Sheffield J, Wood E, Anderson B, Bradbury J, Degaetano A, Troy TJ, Wolfe D. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics, 28(4): 381-407.

He, W., Sengupta M., Velkoff V.A., and DeBarros K.A. 2005. U.S. Census Bureau, Current Population Reports, P23-209, *65+ in the United States: 2005*. U.S. Government Printing Office, Washington, DC.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.): 2001, Climate Change: The Scientific Basis. Contributions of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, 881 pp.

Huntington, T. G., Hodgkins, G. A. and Dudley, R.W. 2003. Historical Trend in River Ice Thickness and Coherence in Hydroclimatological Trends in Maine. *Climatic Change* 61, 217-236.

Huntington, T. G., Hodgkins, G. A., Keim, B. D. and Dudley, R.W. 2004. Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000). *J. Climate* 17, 2626-2636.

IPCC, 1994. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* [Houghton, J.T., L.G. Meira Filho, J.P. Bruce, Hoesung Lee, B.T. Callander, E.F. Haites, N. Harris, and K. Maskell (eds.)]. Cambridge University Press, Cambridge and New York, 339 pp.

IPCC, 2001: Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change [Watson, R.T. and the Core Writing Team (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 398 pp.

IPCC, 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

IPCC, 2007c. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Karl, T.R., Williams, C., Quinlan, F. and Boden, T. 1990. *United States Historical Climatology Network (HCN) Serial Temperature and Precipitation Data*, Environmental Science Division, Publication No. 3404, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 389 pp.

Karl, T.R. and Knight, R.W. 1997. The 1995 Chicago heat wave: How likely is a recurrence. *Bull. Am. Met. Soc.* 78, 1107-1119.

Klein RJT and Tol RSJ. 1997. Adqaptation to climate change: options and technologies an overview paper. Bonn, Germany. United Nations Framework Convention on Climate Change Secretariat. (Technical Paper FCCC/TP/1997/3 p. 33).

Klinenberg E. 2002. Heat Wave: A Social Autopsy of Disaster in Chicago. The University of Chicago Press, Chicago, IL.

Knutson, T.R. and Tuleya, R.E. 2004. Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *J. Climate* 17, 3477-3495.

Kunkel, K.E., Pielke R. Jr. and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bull. Am. Met. Soc.* 80, 1077–1098.

Kunkel, K. E.: 2003, 'North American trends in extreme precipitation', Natural Hazards 29, 291–305.

Kunkel KE, Easterling DR, Hubbard K, Redmond K. 2004. Temporal variations in frost-free season in the United States: 1895–2000. Geophysical Research Letters, 31, L03201, doi:10.1029/2003GL018624, 2004

Landsea CW and Knabb RD. 2007. Tropical Cyclone Wind Probablities: Better Defining Uncertainty at the National Hurricane Center. 19th Conference on Climate Variability and Change.

Lang, Robert (2003) Edgeless Cities: Exploring the Elusive Metropolis. Washington D.C. Brookings Institution Press.

Lang RE and D Chavale. 2004. Micropolitan America: A Brand New Geography. Metropolitan Institute at Virginia Tech Census Note 05:01 May 2004.

Lehtonen M. 2004. The environmental–social interface of sustainable development: capabilities, social capital, institutions. Ecological Economics, 49(2): 199-214.

Lins HG and Slack JR. 1999. Streamflow trends in the United States. Geophysical Research Letters, 26(2): 227-230.

Lins HF and Slack JR. 2005. Seasonal and Regional Characteristics of U.S. Streamflow Trends in the United States from 1940 to 1999. Physical Geography, 26(6): 489-501.

McGheehin MA and M Mirabelli. May 2001. The Potential Impacts of Climate Variability and Change on Temperature-Related Morbidity and Mortality in the United States. Environmental Health Perspectives. 109 (Supplement 2): 185-190.

McGranahan, David (1999) *Natural Amenities Drive Rural Population Change* U.S. Department of Agriculture Economic Research Service Report No. 781.

Meehl, G. A. and Tebaldi, C.: 2004, 'More intense, more frequent, and longer lasting heat waves in the 21st century', Science 305, 994–997.

Meehl, GA, WM Washington, WD Collins, JM Arblaster, A Hu, LE Buja, WG Strand, H Teng. 2005. How Much More Global Warming and Sea Level Rise. Science. Vol 307. pp. 1769-1772.

Meehl GA, Tebaldi C, Teng H, Peterson TC. Current and future U.S. weather extremes and El Niño. Geophysical Research Letters, 34. doi:10.1029/2007GL031027.

Mendelsohn, R and JE Neumann (Eds.). 1999. The Impact of Climate Change on the United States Economy. Cambridge University Press.

Milly PCD, KA Dunne and AV Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438(7066): 347-350.

Moser SC, Roger E. Kasperson, Gary Yohe, and Julian Agyeman. 2007. Adaptation to Climate Change in the Northeast United States: Opportunities, Processes, Constraints in *Mitigation and Adaptation Strategies for Global Change,* special issue entitled: "Northeast United States Climate Impact Assessment" guest edited by: Cameron P. Wake, Peter Frumhoff, James McCarthy, Jerry Melillo, Susanne Moser, Don Wuebbles.

Moss, R.H. and Schneider, S.H., (2000): Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In: Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC [eds. R. Pachauri, T. Taniguchi and K. Tanaka], World Meteorological Organization, Geneva, pp. 33-51.

Nakicenovic, N. et al (2000). *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, U.K., 599 pp. Available online at: http://www.grida.no/climate/ipcc/emission/index.htm

National Synthesis Assessment Team. 2001. *Climate change impacts on the United States: The potential consequences of climate variability and change*. Eds: Melilo, J.M., A.C. Jacentos, T.R. Karl, and the National Assessment Synthesis Team. U.S. Climate Change Research Program, Washington, D.C.

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

National Research Council Division on Earth and Life Studies. 2001. Under the Weather: Climate, Ecosystems, and Infectious Disease. Washington, DC: National Academy Press.

Natural Resources Conservation Service (2007) National Resource Inventory. US Department of Agriculture.

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

National Center for Climatic Data (NCDC). 2007. U.S. Climate at a Glance. Available online at: http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html

Naughton Marie, Alden Henderson, Maria C. Mirabelli, Reinhard Kaiser, John L. Wilhelm, Stephanie M. Kieszak, Carol H. Rubin, and Michael A. McGeehin. (2002) Heat-related mortality during a 1999 heat wave in Chicago. American Journal of Preventive Medicine. 22(4) May 2002, pp. 221-227.

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

Patz, J.A. Health adaptation to climate change: need for far-sighted, integrated approaches. In: *Adapting to climate change: an international perspective*. Smith, J. et al. Eds. New York, USA, Springer-Verlag, pp. 450–464, 1996.

Patz, Jonathan, Samar Khoury and Cindy Parker (2005) Climate Change and Health in California: A Pier Research Roadmap, Report Prepared for the California Energy Commission. CEC-500-2005-093.

Pelling M and High C. Understanding adaptation: What can social capital offer assessments of adaptive capacity? Global Environmental Change, Part A: Human and Policy Dimensions [Global Environ. Change (A Hum. Policy Dimens.)]. Vol. 15, no. 4, pp. 308-319. Dec 2005.

Piechota, T, J Timilsena, G Tootle, H. Hidalgo. (10 August 2004). The Western U.S. Drought: How Bad is It? EOS Transatctions and American Geophysical Union. Vol 85 No 342. pp. 301-308.

Pielke, R. A., Jr., and R. A. Pielke Sr., 1997: Hurricanes: Their nature and impacts on society. John Wiley and Sons, 279 pp.

Public Law 101-606. "Global Change Research Act of 1990".

Puentes, Robert and David Warren (2006) One Fifth of America, A Comprehensive Guide to America's First Suburbs. Brookings Metropolitan Policy Program

Rebhun, Uzi and Adi Raveh (2006) The Spatial Distribution of Quality of Life in the United States and Interstate Migration, 1965–1970 AND 1985–1990. *Social Indicators Research*. 78 pp. 137–178.

Rignot, E. 2006. Changes in ice dynamics and mass balance of the Antarctic ice sheet. *Phil. Trans. Royal Society* 364, 1637-1655.

Rose, Joan B., Paul R. Epstein, Erin K. Lipp, Benjamin H. Sherman, Susan M. Bernard, and Jonathan A. Patz. (2001). Climate Variability and Change in the United States: Potential Impacts on Water- and Foodborne Diseases by Microbiological Agents. *Environmental Health Perspectives* 109: Suppl 2, 211-220.

Rosenthal, Joyce Klein, Paul W Brandt-Rauf (2006) Damage and low income households, Environmental Planning and Urban Health Annals Academy of Medicine. 35(8) pp. 517-522

Rosenzweig, C and WD Solecki (Eds.). July 2001. Climate Change and a Global City: The Potential Consequences of Climate Variability and Change: Metro East Coast. New York City: Columbia Earth Institute: Columbia University.

Ross, T. and N. Lott. 2000. *A climatology of recent extreme weather and climate events.* National Climatic Data Center, Technical Report 2000-02, 18 pp.

Schar C, Vidale PL, Luthi D, Frei C, Haberli C, Liniger MA, Appenzeller C. 2004. The role of increasing temperature variability in European summer heatwaves. Nature, 427: 332-336.

Scheraga, Joel D., K.L. Ebi, A.R. Moreno, and John Furlow, "From Science to Policy: Developing Responses to Climate Change," in Climate Change and Human Health: Risks and Responses (Eds. A.J. McMichael et. al), WHO, WMO, UNEP, 2003.

Scheraga, JD and AE Grambsch, 1998. Risks, Opportunities and Adaptation to Climate Change. *Climate Research* 10: 85-95.

Seager R, 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

Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, W.D., Howe, H.L., Wilhelm, J.L.: 1996, 'Heat-related deaths during the July 1995 heat wave in Chicago. *New Eng. J. Medicine* 335, 84-90.

Serow, William J. (2001) Retirement Migration Counties in the Southeastern United States: Geographic, Demographic, and Economic Correlates. *The Gerontologist.* 41(2) pp. 220–22

State of California, Department of Finance, (2004) Population Projections by Race/Ethnicity, Gender and Age for California and Its Counties 2000-2050, Sacramento, California

Stewart, I.T., Cayan, D.R. and Dettinger, M.D. 2005. Changes toward earlier stream flow timing across western North America. *J. Climate* 18, 1136-1155.

Stott, P.A. 2004. Human contribution to the European heat wave of 2003. *Nature* 432, 610-614.

Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA. 2006. Going to the Extremes: An Intercomparison of Model-Simulated Historical and Future Changes in Extreme Events. Climatic Change, 79(3-4): 185-211.

Tol R. 1998. Socio-economic scenarios. In: *UNEP Handbook on Methods for Climaste Change Impact Assessment and Adaptation Studies* [Burton, I., J.F. Feenstra, J.B. Smith, and R.S.J. Tol (eds.)] Version 2.0, United Nations Environment Programme and Institue for Environmental Stuides, Vrije Universiteit, Amsterdam, The Netherlands, Chpater 2, pp. 1-19. Availabel online at http://www.vu.nl/english/o_o/instituten/IVM/research/climatechange/Handbook.htm

US BEA, 2008. Survey of Current Business. Vol. 88, No. 3.

U.S. Census Bureau, Demographic Trends in the 20th Century, November 2002, CENSR-4.

U.S. Census Bureau. 2000. Population Projections of the United States by Age, Sex, Race, Hispanic Origin, and Nativity: 1999 to 2100., February 14, 2000.

U.S. Census Bureau, 2000. Methodology and Assumptions for the Population Projections of the United States.

US Census Bureau. 2005. Florida, California and Texas to Dominate Future Population Growth, Census Bureau Reports. Available at: http://www.census.gov/Press-Release/www/releases/archives/population/004704.html.

U.S. Census Bureau, 2006. *Statistical Abstract of the United States: 2007* (126th Edition) Washington, DC.

U.S. Climate Change Science Program and the Subcommittee on Global Change Research. 2003. Strategic Plan for the U.S. Climate Change Science Program.

U.S. Department of Energy. Trend in Residential Air-Conditioning Usage from 1978 to 1997. www.eka.doe.gov/eneu/consumptionbriefs/recs/actrends/recs ac trends.html.

USDA Natural Resources Conservation Service, National Water and Climate Center, http://www.wcc.nrcs.usda.gov/cgibin/rs.pl (reservoir data)

U.S. National Research Council Committee on the Analysis of Global Change Assessments. 2007. Analysis of Global Change Assessments: Lessons Learned. Washington, D.C.: National Academy Press.

Webster, P.J., Holland, G.J., Curry, J.A. and Chang, H.R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309, 1844-1846.

Weisler RH, JG Barbee IV, MH Townsend. 2006. Mental Health and Recovery in the Gulf Coast After Hurricanes Katrina and Rita. 2007. JAMA, August 2, 2006, Vol 296, Vo 5, 585-588.

Westerling AL, HG Hidalgo, DR Cayan, TW Swetnam. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science. 18 August 2006. Vol 313. No. 5789, pp. 940-943.

Whitman, S., Good, G., Donoghue, E.R., Benbow, N., Shou, W.Y. and Mou, S.X. 1997. Mortality in Chicago attributed to the July 1995 heat wave. *Am. J. Public Health* 87, 1515-1519.
Williams, C. N., M. J. Menne, R. S. Vose, and D. R. Easterling, 2007. United States Historical Climatology Network Monthly Temperature and Precipitation Data. ORNL/CDIAC-87, NDP-019. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

WHO. 2003. Climate change and human health - risks and responses. Editors: McMichael A.J., D.H. Campbell-Lendrum, C.F. Corvalán, K.L. Ebi, A. Githeko, J.D. Scheraga and A. Woodward. WHO, UNEP, WMO.

Yohe, G.W., R.D. Lasco, Q.K. Ahmad, N.W. Arnell, S.J. Cohen, C. Hope, A.C. Janetos and R.T. Perez, 2007: Perspectives on climate change and sustainability. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 811-841

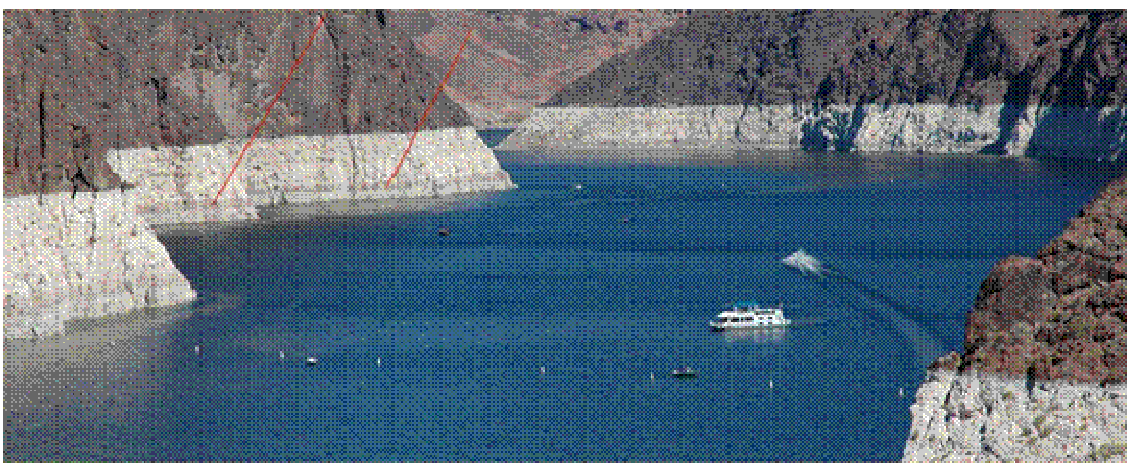
1.7 Boxes

Box 1.1 Potential impacts of heat and droughts: wildfires and reservoir levels

Two of the projected changes in climate -- increased temperatures and droughts -- can increase the risks of wildfires and water shortages. Fire frequency is correlated with temperature, fuel loads and fuel moisture. Periods of drought followed by weeks of extreme heat and low humidity provide ideal conditions for fire. Westerling *et al.* (2006) compiled a database of large wildfires in western United States forests since 1970 and compared them with hydroclimatic and land-surface data. They find that large wildfire activity increased suddenly and markedly in the mid-1980's with higher large-wildfire frequency and longer fire duration and season (Westerling, *et.al.*, 2006). The greatest increases in wildfires have occurred in mid-elevation forests in the Northern Rockies, and are strongly associated with increased spring and summer temperatures and earlier spring snowmelt (CCSP, 2008).

Droughts continue to be exacerbated by earlier spring snowmelt run-off in the mountainous West, which results in less water available in late summer. In addition, widespread declines in springtime snow water equivalent in the West have occurred over the period 1925–2000, especially since mid-century. Because high-elevation snow pack contributes approximately 70% of the annual runoff in the Colorado River Basin, these changes pose significant risks of water shortages. Water levels have fallen in recent years in reservoirs across the West. For example, Lake Mead, the largest man-made lake in the United States, has historically provided a steady water supply for the Colorado River Basin. However, drought conditions and decreased runoff have threatened the lake's supplies. The duration of drought conditions in the Colorado River system is similar in extent to a drought experienced in the late 1950s. As of October 2006, the lake was at 51% of capacity, with a surface area is 100,000 acres which is significantly less than the lake's maximum surface area of 162,700 acres. It is estimated that as a result of the 1999-2004 drought and increased water resources extraction, Lake Mead and Lake Powell will take 13 to 15 years of average flow conditions to refill.

Lake Mead Elevation at Hoover Dam



Source: Ken Dewey, High Plains Regional Climate Center and National Drought Mitigation Center. October 31, 2006. (http://www.hprcc.unl.edu/nebraska/Lake-Mead-2006.html)

1.8 Tables

Table 1.2 Description of likelihood: probabilistic assessment of outcome having occurred or occurring in the future based on quantitative analysis or elicitation of expert views.

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

1.9 Figures

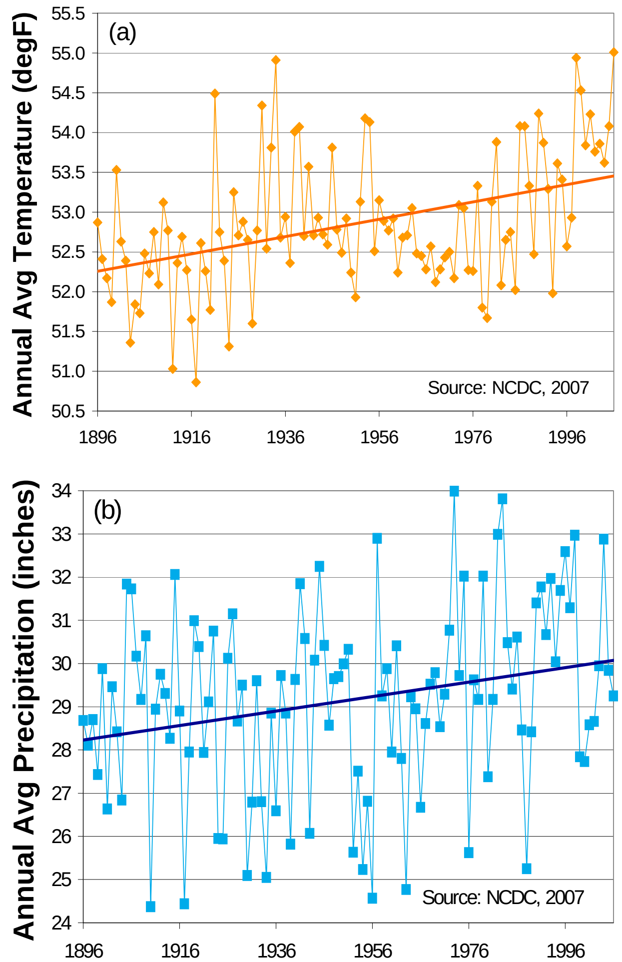
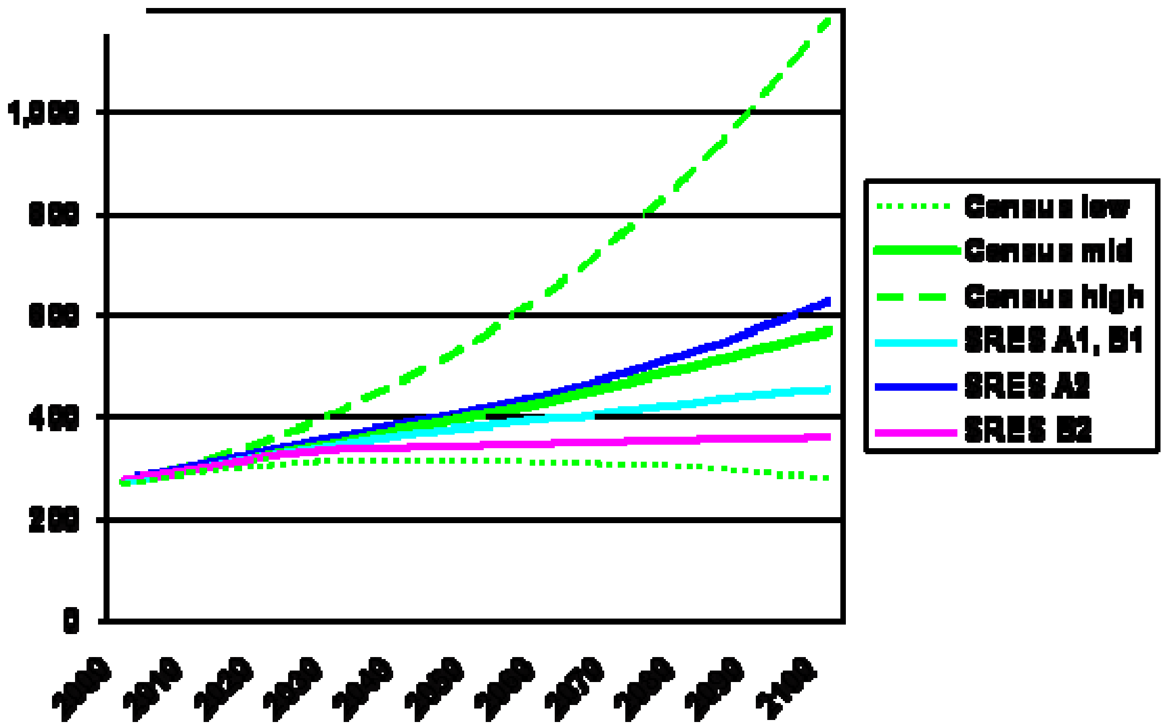


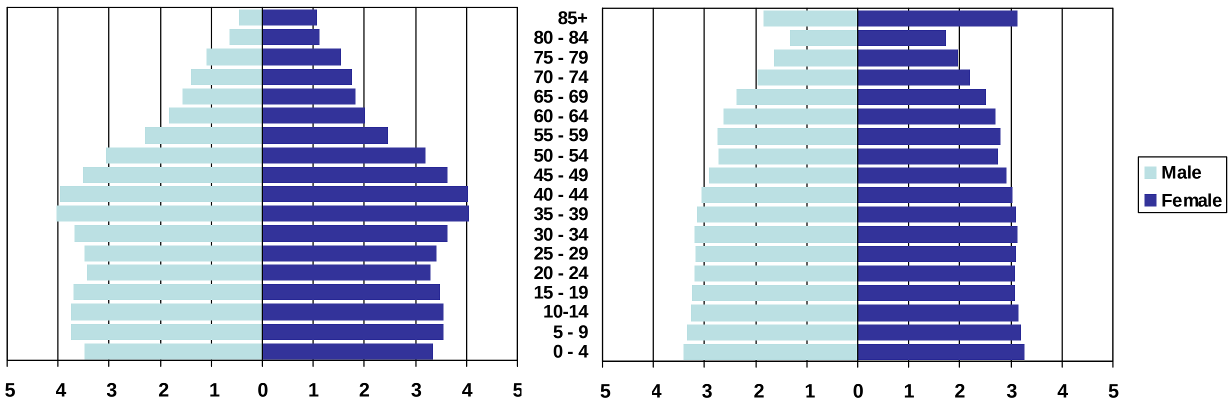
Figure 1.1 Observed trends in annual average (a) temperature (^{o}F) and (b) precipitation (inches) across the continental United States from 1896 to 2006 (Source: NCDC, 2007)

Figure 1.2 US Population Projections 2000-2100.



Data sources: Census Population Projections http://www.census.gov/population/www/projections/natsum-T1.html
SRES Population Projections: http://sres.ciesin.columbia.edu/tgcia/

Figure 1.3 Population Pyramids of the US 2000 and 2050 (Interim Projections based on 2000 Census)



Data source: Census Population Projections http://www.census.gov/ipc/www/usinterimproj/

Figure 1.4: 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).

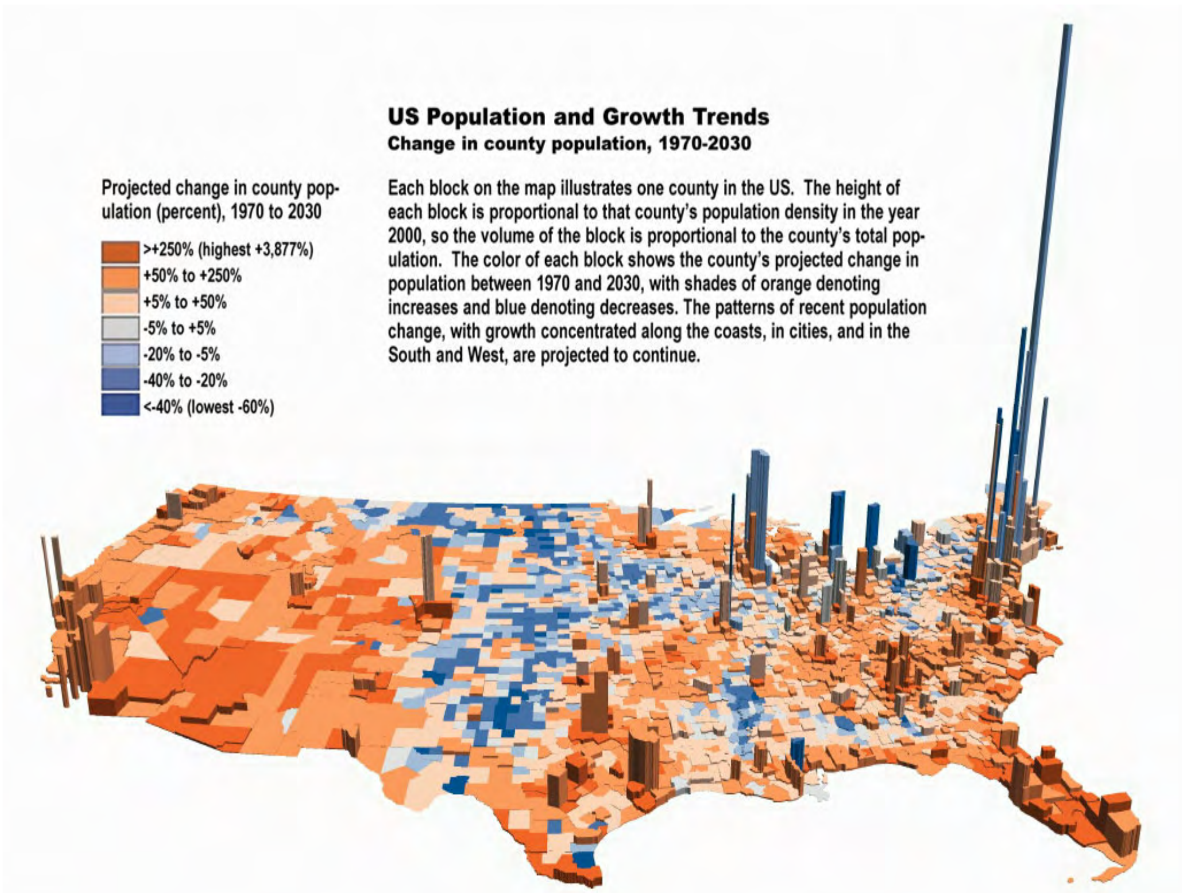
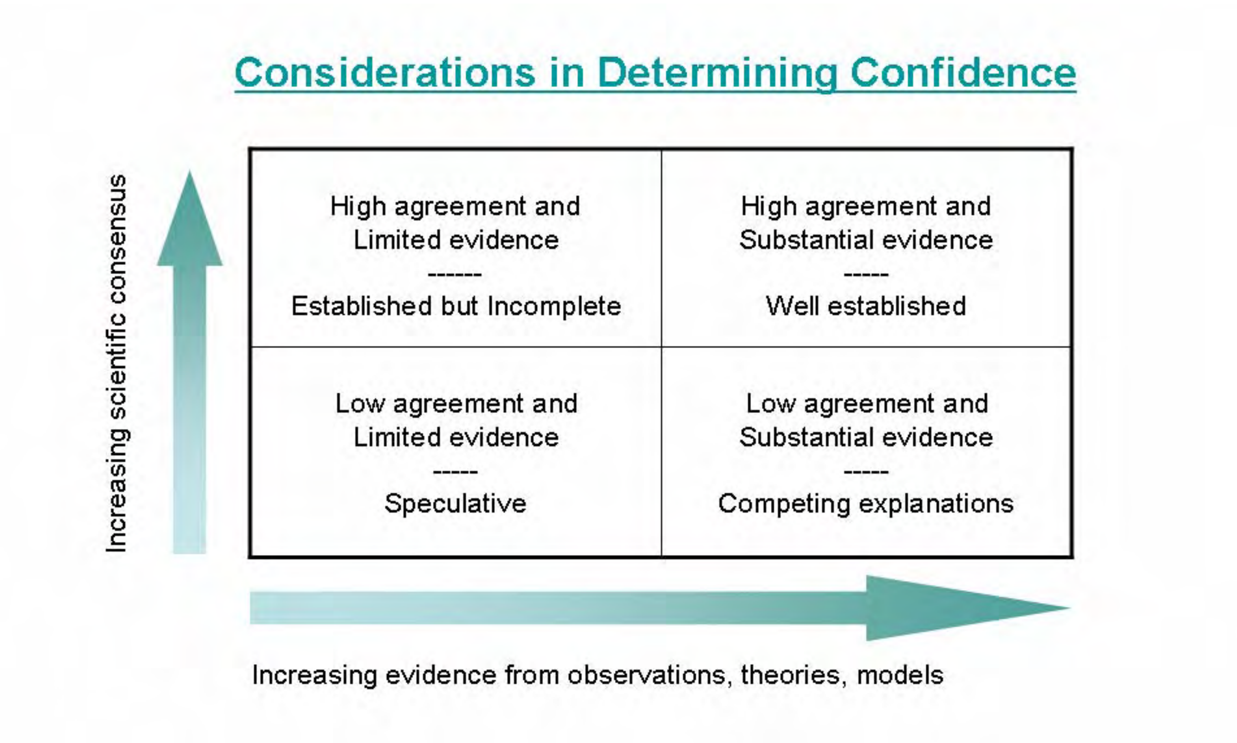


Figure 2.5 Considerations in determining confidence.



Synthesis and Assessment Product 4.6

Chapter 2: Effects of Global Change on Human Health

Lead Author: Kristie L. Ebi, ESS, LLC

Contributing Authors: John Balbus, Environmental Defense; Patrick L. Kinney, Columbia University; Erin Lipp, University of Georgia; David Mills, Stratus Consulting; Marie S. O'Neill, University of Michigan; Mark Wilson, University of Michigan

Table of Contents

2.1 Introduction

Climate change can affect health directly and indirectly. Directly, extreme weather events (floods, droughts, windstorms, fires, and heatwaves) can affect the health of Americans and cause significant economic impacts. Indirectly, climate change can alter or disrupt natural systems, making it possible for vector, water-, and foodborne diseases to spread or emerge in areas where they had been limited or not existed, or for such diseases to disappear by making areas less hospitable to the vector or pathogen (NRC, 2001). Climate also can affect the incidence of diseases associated with air pollutants and aeroallergens[1]. (Bernard *et al*., 2001) The cause-and-effect chain from climate change to changing patterns of health outcomes is often complex and includes factors such as initial health status, financial resources, effectiveness of public health programs, and access to medical care. Therefore, the severity of future impacts will be determined by changes in climate as well as by concurrent changes in nonclimatic factors and by adaptations implemented to reduce negative impacts.

A comprehensive assessment of the potential impacts of climate 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 (Bernard *et al*., 2001). However, uncertainties in climate models make the direction and degree of change speculative (Bernard and Ebi, 2001).
- Federal and State laws and regulatory programs protect much of the U.S. population from waterborne disease. However, if climate variability increases, current and future deficiencies in areas such as watershed protection, infrastructure, and storm drainage systems will probably increase the risk of contamination events (Rose *et al.*, 2000).
- It is unlikely that vector- and rodent-borne diseases will cause major epidemics in the 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).

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

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

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

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

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

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

2.2 Observed Climate-Sensitive Health Outcomes in the U.S.

2.2.1 Thermal Extremes: Heat Waves

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

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

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

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

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

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

2.2.2 Thermal Extremes: Cold Waves

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

Because climate change is projected to reduce the severity and length of the winter season (Alley *et al*., 2007), there is widespread speculation that cold-related mortality will decrease. However, many factors contribute to winter mortality, making highly uncertain how climate change could affect mortality. No projections have been published for the U.S. that incorporate critical factors, such as the influence of influenza outbreaks.

2.2.3 Extreme Events: Hurricanes, Floods, and Wildfires

The United States experiences a wide range of extreme weather events, including hurricanes, floods, tornadoes, blizzards, windstorms, and drought. Other extreme events, such as wildfires, are strongly influenced by meteorological conditions. Direct morbidity and mortality due to an event increase with the intensity and duration of the event, and can decrease with advance warning and preparation. Health also can be affected indirectly. Examples include carbon monoxide poisonings from portable electric generator use following hurricanes (CDC, 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 2.2 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 to hurricanes in 2005 (NOAA, 2007b). From 1940 through 2005 roughly 4,300 lives were lost in the U.S. to hurricanes. The impact of the 2005 hurricane season is especially notable as it doubled the estimate of the average number of lives lost to hurricanes in the U.S. over the previous 65 years.

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

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

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

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

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

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

2.2.4 Indirect Health Impacts of Climate Change

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

2.2.4.1 Vectorborne and Zoonotic (VBZ) Diseases

Transmission of infectious agents by blood-feeding arthropods (particular insect or tick species) and/or by non-human vertebrates (certain rodents, canids, and other mammals) has changed significantly in the 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). While increasing average temperatures may allow the permissive range for *Aedes aegypti*, the mosquito vector of dengue virus, to move further north in the US, it is unlikely that more cases of dengue fever will be observed because most people are protected while living indoors due to quality housing. Indeed, a recent epidemic of dengue in southern Texas and northern Mexico produced many cases among the relatively poor Mexicans, and very few cases among Texans (Reiter *et al.* 1999). At the same time, other diseases reported their distribution either because of suitable environmental conditions (including climate) or enhanced detection (examples include Lyme disease, ehrlichioses, and Hantavirus pulmonary syndrome) or were introduced and are expanding their range due to appropriate climatic and ecosystem conditions (West Nile Virus; e.g. Reisen *et al.* 2006). Still others are associated with non-human vertebrates that have complex associations with climate variability and human disease (e.g. plague, influenza). The burden of VBZ diseases in the 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 the abundance and distributions of vectors that may carry West Nile virus, Western Equine encephalitis, Eastern Equine encephalitis, Bluetongue virus, and Lyme disease. Climate also may affect disease risk, but sometimes in counter-intuitive ways that do not necessarily translate to increased disease incidence (Wegbreit and Reisen, 2000; Subak, 2003; McCabe and Bunnell, 2004; DeGaetano, 2005; Purse *et al.*, 2005; Kunkel *et al.*, 2006; Ostfeld *et al.*, 2006; Shone *et al.*, 2006). Changes in other factors such as hosts, habitats, and human behavior are also important.

2.2.4.2 Waterborne and Foodborne Diseases

Water and foodborne diseases continue to cause significant morbidity in the 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). Similarly in drinking water outbreaks of known etiology, bacteria were the most commonly identified agent (29%, primarily *Campylobacter*), followed by parasites and viruses (each identified 5% of the time) (2003 – 2004; Liang *et al.*, 2006). Gastroenteritis continues to be the primary disease associated with food and water exposure. In 2003 and 2004, gastroenteritis was noted in 48% and 68% of reported recreational and drinking water outbreaks, respectively (Dziuban *et al.*, 2006; Liang *et al.*, 2006).

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

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

Studies in North America (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). Pathogenic species of *Campylobacter* cannot replicate in the environment and will not persist long under non-microaerophilic conditions, suggesting that high ambient temperatures would not contribute to increased replication in water or in food products.

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

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

The most striking example of an increased range in pathogen distribution and incidence was documented in 2004, when an outbreak of shellfish-associated *V. parahaemolyticus* was reported from Prince William Sound in Alaska (McLaughlin *et al.*, 2005). *V. parahaemolyticus* had never been isolated from Alaskan shellfish before and it was thought that Alaskan waters were too cold to support the species (McLaughlin *et al.*, 2005). In the period preceding the July 2004 outbreak, water temperatures in the harvesting area consistently exceeded 15^{o} C and the mean daily water temperatures were significantly higher than in the prior six years (McLaughlin *et al.*, 2005). This outbreak extended the northern range of oysters known to contain *V. parahaemolyticus* and cause illness by 1,000 km. Given the well-documented association between increasing sea surface temperatures and proliferation of many *Vibrio* species, evidence suggests that increasing global temperatures will lead to an increased burden of disease associated with certain *Vibrio* species in the U.S., 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 of cryptosporidiosis per 100,000 people 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 to a slight lag in reporting (Dietz and Roberts 2000; Furness *et al.*, 2000; Casman *et al.*, 2001). With increasing global temperatures, an increase in recreational use of water can be reasonably expected and could lead to increased exposure among certain groups, especially children.

Naegleria fowleri is a free-living amboeboflagellate found in lakes and ponds at warm temperatures, either naturally or in thermally polluted bodies of water. While relatively rare, infections are almost always fatal (Lee *et al.*, 2002). *N. fowleri* can be detected in environmental waters at rates up to 50% (Wellings *et al.*, 1977) at water temperatures above 25°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 could increase this pathogen's range.

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

An analysis of waterborne outbreaks associated with drinking water in the United States between 1948 and 1994 found that 51% of outbreaks occurred following a daily precipitation event in the 90th percentile and 68% occurred when precipitation levels reached the 80th percentile (Curriero *et al.*, 2001) (Figure 2.4). Similarly, Thomas *et al.* (2006) found that the risk of waterborne disease doubled when rainfall amounts surpassed the 93rd percentile. Rose *et al.* (2000) found that the relationship between rainfall and disease was stronger for surface water outbreaks, but the association was significant for both surface and groundwater sources. In 2000, groundwater used for drinking water in Walkerton, Ontario was contaminated with *E. coli* O157:H7 and *Campylobacter* during rains that surpassed the 60-year event mark for the region and the 100-year event mark in local areas (Auld *et al.*, 2004). In combination with preceding record high temperatures, 2,300 people in a community of 4,800 residents became ill (Hrudey *et al.*, 2003; Auld *et al.*, 2004).

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

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

2.2.4.3 Influenza

Influenza may be considered a zoonosis in that pigs, ducks, etc. serve as non-human hosts to the influenza viruses (e.g. H3N2, H1N1) that normally infect humans (not H5N1). A number of recent studies evaluated the influence of weather and climate variability on the timing and intensity of the annual influenza season in the 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 Niño years increased hospital admissions for viral pneumonia (Ebi *et al.*, 2001). In an attempt to better understand the spatio-temporal patterns of ENSO and influenza, Choi *et al.* (2006) used stochastic models (mathematical models that take into account the presence of randomness) to analyze California county-specific influenza mortality, and produced maps that showed different risks during the warm and cool phases. In general, these studies of influenza further support the importance of climate drivers at a global and regional scale, but have not advanced our understanding of underlying mechanisms.

2.2.4.4 Valley Fever

Valley fever (Coccidioidomycosis) is an infectious disease caused by inhalation of the spores of a soil-inhabiting fungus that thrives during wet periods following droughts. The disease is of public health importance in the desert southwest. In the early 1990s, California experienced an epidemic of Valley Fever following five years of drought (Kolivras and Comrie, 2003). Its incidence varies seasonally and annually, which may be partly due to climatic variations (Kolivras and Comrie, 2003; Zender and Talamantes, 2006). If so, then climate change could affect its incidence and geographic range.

2.2.4.5 Morbidity and Mortality Due to Changes in Air Quality

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

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

PM2.5 is a far more complex pollutant than ozone, consisting of all airborne solid or liquid particles that share the property of being less than 2.5 micrometers in aerodynamic diameter.[2] All such particles are included, regardless of their size, composition, and biological reactivity. PM2.5 has complex origins, including primary particles directly emitted from sources and secondary particles that form via atmospheric reactions of precursor gases. Most of the particles captured as PM2.5 arise from burning of fuels, including primary particles such as diesel soot and secondary particles such as sulfates and nitrates. Epidemiologic studies have demonstrated associations between both short-term and long-term average ambient concentrations and a variety of adverse health outcomes including respiratory symptoms such as coughing and difficulty breathing, decreased lung function, aggravated asthma, development of chronic bronchitis, heart attack, and arrhythmias (Dockery *et al.*, 1993; Samet *et al.*, 2000; Pope *et al.*, 1995, 2002, 2004; Pope and Dockery 2006; Dominici et al, 2006; Laden *et al.*, 2006). Associations have also been reported for increased school absences, hospital admissions, emergency room visits, and premature mortality. Susceptible individuals include people with existing heart and lung disease, and diabetics, children, and older adults. Because the mortality risks of PM2.5 appear to be mediated through narrowing of arteries and resultant heart impacts (Künzli *et al*., 2005), persons or populations with high blood pressure and/or pre-existing heart conditions may be at increased risk. In a study of mortality in relation to long-term PM2.5 concentrations in 50 U.S. cities, individuals without a high school education demonstrated higher concentration/response functions that those with more education (Pope *et al*., 2002). This result suggests that low education was a proxy for increased likelihood of engaging in outdoor labor with an associated increase in exposure to ambient air.

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

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

2.2.4.6 Aeroallergens and Allergenic Diseases

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

2.3 Projected Health Impacts of Climate Change in the U.S.

2.3.1 Heat-Related Mortality

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

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

Table 2.1 summarizes projections of temperature-related mortality either in the U.S. or in temperate countries whose experience is relevant to the U.S. (Dessai 2003)[3] (Woodruff *et al.* 2005) (Knowlton *et al.* 2007) (CLIMB 2004; Hayhoe *et al.* 2004). Similar studies are underway in Europe (Kosatsky *et al.* 2006; Lachowsky and Kovats 2006). All studies used downscaled projections of future temperature distributions in the geographic region of interest. The studies used different approaches to incorporate likely future adaptation, addressing such issues as increased availability of air conditioning, heatwave early warning systems, demographic changes, and enhanced services such as cooling shelters and physiological adaptation.

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

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

2.3.2 Hurricanes, Floods, Wildfires and Health Impacts

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

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

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

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

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

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

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

2.3.3 Vectorborne and Zoonotic Diseases

Modeling the possible impacts of climate change on VBZ diseases is complex, and few studies have made projections for diseases of concern in the 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 to decrease the geographic range of TBE in areas of lower latitude and elevation as transmission expands northward (Randolph and Rogers, 2000).

2.3.4 Water- and Foodborne Diseases

Several important pathogens that are commonly transmitted by food or water may be susceptible to changes in replication, survival, persistence, habitat range, and transmission under changing climatic and environmental conditions (Table 2.2). Many of these agents show seasonal infection patterns (indicating potential underlying environmental or weather control), are capable of survival or growth in the environment, or are capable of waterborne transport. Factors that may affect these pathogens include changes in temperature, precipitation, extreme weather events (i.e., storms), and ecological shifts.

2.3.5 Air Quality Morbidity and Mortality

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

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

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

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

Several studies explored the impacts of climate change alone on future ozone projections. In a coarse-scale analysis of pollution over the continental 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 2.5) (Hogrefe *et al.*, 2004b). The influence of climate on mean ozone values was similar in magnitude to the influence of rising global background by the 2050s, but climate had a much greater impact on extreme values than did the global background. When biogenic VOC emissions were allowed to increase in response to warming, an additional increase in ozone concentrations was projected that was similar in magnitude to that of climate alone (Hogrefe *et al.*, 2004b). Climate change shifted the distribution of ozone concentrations towards higher values, with larger relative increases in future decades (Figure 6).

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

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

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

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

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

The New York Climate and Health Project examined the marginal sensitivity of health to changes in climate to project the potential health impacts of ozone in the eastern 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%. In addition, ozone red alert days could increase by 68%. Changes in health impacts were of corresponding magnitude.

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

- There is an established but incomplete level of knowledge suggesting that both ozone and fine particle concentrations may be affected by climate change.

- A substantial body of new evidence on ozone supports the interpretation that ozone concentrations would be more likely to increase than decrease in the U.S. as a result of climate change, holding precursor emissions constant.

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

2.4 Vulnerable Regions and Subpopulations

In adapting the IPCC's definitions[4] to public health, "vulnerability" can be defined as the summation of all risk and protective factors that ultimately determine whether an individual or subpopulation experiences adverse health outcomes, and "sensitivity" can be defined as an individual's or subpopulation's increased responsiveness, primarily for biological reasons, to a given exposure. Thus, specific subpopulations may experience

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

heightened vulnerability for climate-related health effects for a wide variety of reasons. Biological sensitivity may be related to the developmental stage, presence of pre-existing chronic medical conditions (such as the sensitivity of people with chronic heart conditions to heat-related illness), acquired factors (such as immunity), and genetic factors (such as metabolic enzyme subtypes that play a role in sensitivity to air pollution effects). Socioeconomic factors also play a critical role in altering vulnerability and sensitivity to environmentally-mediated factors. They may alter the likelihood of exposure to harmful agents, interact with biological factors that mediate risk (such as nutritional status), and/or lead to differences in the ability to adapt or respond to exposures or early phases of illness and injury. For public health planning, it is critical to recognize populations that may experience synergistic effects of multiple risk factors for health problems related to climate change and to other temporal trends.

2.4.1 Vulnerable Regions

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

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

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

2.4.2 Specific Subpopulations at Risk

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

2.4.2.1 Children

Children's small body mass to surface area ratio and other factors make them more vulnerable to heat-related morbidity and mortality (AAP, 2000), while their increased breathing rates relative to body size, time spent outdoors, and developing respiratory tracts heighten their sensitivity to harm from ozone air pollution (AAP, 2004). In addition, children's relatively naïve immune systems increase the risk of serious consequences from water and foodborne diseases; specific developmental factors make them more vulnerable to complications from specific severe infections like *E Coli* O157:H7.

Children's lack of immunity also plays a role in higher risk of mortality from malaria (CDC, 2004b). Conversely, maternal antibodies to dengue in infants convey increased risk of developing dengue hemorrhagic syndromes. A second peak of greater risk of complications from dengue appears in children between the ages of 3 and 5 (Guzman and Khouri, 2002).

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

2.4.2.2 Older Adults

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

2.4.2.3 Impoverished Populations

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

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

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

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

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

2.4.2.4 People with chronic conditions and mobility and cognitive constraints

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

2.4.2.5 Occupational groups

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

2.4.2.6 Recent migrants and immigrants

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

2.5 Adaptation

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

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

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

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

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

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

2.5.1 Actors and Their Roles and Responsibilities for Adaptation

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

Additional research and development are needed to ensure that surveillance systems account for and anticipate the potential effects of climate change. 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 and 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).

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

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

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

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

2.5.2 Adaptation Measures to Manage Climate Change-Related Health Risks

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

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

2.6 Conclusions

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

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

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

2.7 Expanding the Knowledge Base

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

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

- Improve characterization of exposure-response relationships, particularly at regional and local levels, including identifying thresholds and particularly vulnerable groups.

- Collect data on the early effects of changing weather patterns on climate-sensitive health outcomes.

- Collect and enhance long-term surveillance data on health issues of potential concern, including vectorborne and zoonotic diseases, air quality, pollen and mold counts, reporting of food- and waterborne diseases, morbidity due to temperature extremes, and mental health impacts from extreme weather events.

- Develop quantitative models of possible health impacts of climate change that can be used to explore the consequences of a range of socioeconomic and climate scenarios.

- Increase understanding of the processes of adaptation, including social and behavioral dimensions, as well as the costs and benefits of interventions.

- Evaluate the implementation of adaptation measures. For example, evaluation of heatwave warning systems, especially as they become implemented on a wider scale (NOAA, 2005), is needed to understand how to motivate appropriate behavior.

- Understand local and regional scale vulnerability and adaptive capacity to characterize the potential risks and the time horizon over which climate risks might arise; these assessments should include stakeholders to ensure their needs are identified and addressed in subsequent research and adaptation activities.

- Improve comprehensive estimates of the co-benefits of adaptation and mitigation policies in order to clarify trade-offs and synergies.

- Improve collaboration across the multiple agencies and organizations with responsibility and research related to climate change-related health impacts, such as weather forecasting, air and water quality regulations, vector control programs, and disaster preparation and response.

- Anticipate infrastructure requirements that will be needed to protect against extreme events such as heatwaves, and food- and waterborne diseases, or to alter urban design to decrease heat islands, and to maintain drinking and wastewater treatment standards and source water and watershed protection.

Develop downscaled climate projections at the local and regional scale in order to conduct the types of vulnerability and adaptation assessments that will enable adequate response to climate change and to determine the potential for interactions between climate and other risk factors, including societal, environmental, and economic. The growing concern over impacts from extreme events demonstrates the importance of climate models that allow for stochastic generation of possible future events, to assess not only how disease and pathogen population dynamics might respond, but also to assess whether levels of preparedness are likely to be adequate.

2.8 References

American Academy of Pediatrics (AAP) Committee on Sports Medicine and Fitness, 2000: Climatic heat stress and the exercising child and adolescent. *Pediatrics*, **106(1),** 158-159.

American Academy of Pediatrics (AAP), 2004: Ambient air pollution: health hazards to children. *Pediatrics*, **114(6),** 1699-1707.

Angell S.Y., and M.S. Cetron. 2005: Health disparities among travelers visiting friends and relatives abroad. *Annals of Internal Medicine*, **142**, 67-72.

Auld, H., D. MacIver, and J. Klaassen, 2004: Heavy rainfall and waterborne disease outbreaks: the Walkerton example. *Journal of Toxicology and Environmental Health, Part A*, **67,** 1879-1887.

Aw, J. and M.J. Kleeman, 2003: Evaluating the first-order effect of inter-annual temperature variability on urban air pollution. *Journal of Geophysical Research*, **108,** 7-1 - 7-18

Bacaner N, B Stauffer, D.R. Boulware, P.F. Walker, J.S. Keystone, 2004: Travel medicine considerations for North American immigrants visiting friends and relatives. *Journal of the American Medical Association,* **291***, 2856-64.*

Balling Jr., R.C. and R.S. Cerveny, 2003: Compilation and discussion of trends in severe storms in the United States: popular perception v. climate reality. *Natural Hazards,* **29,** 103-112.

Basu, R., F. Dominici, and J.M. Samet, 2005: Temperature and mortality among the elderly in the United States: a comparison of epidemiologic methods. *Epidemiology,* **16(1),** 58-66.

Bates, D.V., 2005: Ambient ozone and mortality. *Epidemiology*, **16(4),** 427-429.

Beggs, P.J. and H.J. Bambrick, 2005: Is the global rise of asthma an early impact of anthropogenic climate change? *Environmental Health Perspectives*, **113**, 915-9.

Bell, M. and H. Ellis, 2004: Sensitivity analysis of tropospheric ozone to modified biogenic emissions for the Mid-Atlantic region. *Atmospheric Environment,* **38(1),** 879–1889.

Bell, M.L., R. Goldberg, C Hogrefe, P.L. Kinney, K. Knowlton, B. Lynn, J. Rosenthal, C. Rosenzweig, and J. Patz, 2007: Climate change, ambient ozone, and health in 50 U.S. cities. *Climatic Change*.

Bell, ML, A McDermott, SL Zeger, JM Samet, F Dominici. 2004. Ozone and mortality in 95 U.S. urban communities, 1987 to 2000. *Journal of the American Medical Association* 292: 2372-8.

Bernard, S.M. and K.L. Ebi, 2001: Comments on the process and product of the health impacts assessment component of the national assessment of the potential consequences of climate variability and change for the United States. *Environmental Health Perspectives,* **109(2),** 177-184.

Bharti, A.R., J.E. Nally, J.N. Ricladi, M.A. Matthias, M.M. Diaz, M.A. Lovett, P.N. Levett, R.H. Gilman, M.R. Willig, E. Gotuzzo, and J.M. Vinetz, 2003: Leptospirosis: a zoonotic disease of global importance. *The Lancet Infectious Diseases,* **3,** 757-771.

Braga, A.L., A. Zanobetti, and J. Schwartz, 2001: The time course of weather related deaths. *Epidemiology*, **12,** 662-667.

Bronstert, A. 2003. Floods and climate change: interactions and impacts. *Risk Analysis* **23(3)**:545-557.

Brown, T. J., B. L. Hall, and A. L. Westerling. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. *Climatic Change,* **62**:365-388.

Brownstein, J.S., T.R. Holford, and D. Fish, 2003: A climate-based model predicts the spatial distribution of the Lyme disease vector Ixodes scapularis in the United States. *Environmental Health Perspectives*, **111(9),** 1152-1157.

Brownstein, J.S., T.R. Holford, and D. Fish, 2004: Enhancing West Nile virus surveillance, United States. *Emerging Infectious Diseases*, **10,** 1129-1133.

Burkhardt, W. and K.R. Calci, 2000: Selective accumulation may account for shellfish-associated viral illness. *Applied and Environmental Microbiology,* **66(4)**, 1375-1378.

Burr, M.L., J.C. Emberlin, R. Treu, S. Cheng and N.E. Pearce, 2003: Pollen counts in relation to the prevalence of allergic rhinoconjunctivitis, asthma and atopic eczema in the International Study of Asthma and Allergies in Childhood (ISAAC). *Clin. Exp. Allergy,* **33**, 1675-80.

Cabanes, P.E., F. Wallett, E. Pringuez, and P. Pernin, 2001: Assessing the risk of primary amoebic meningoencephalitis from swimming in the presence of environmental *Naegleria fowleri*. *Applied and Environmental Microbiology,* **67(7),** 2927-2931.

Callaghan, W.M., *et al.*, 2007: Health concerns of women and infants in times of natural disasters: lessons learned from Hurricane Katrina. *Maternal and Child Health Journal*.

Carson, C., S. Hajat, B. Armstrong, and P. Wilkinson, 2006: Declining vulnerability to temperature-related mortality in London over the 20th century. *American Journal of Epidemiology,* **164(1),** 77-84.

Casassa, G., C. Rosenzweig, A. Imeson, D.J. Karoly, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin and P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hansson CE (Eds). Cambridge University Press, Cambridge, U.K.

Casman, E., B. Fischhoff, M. Small, H. Dowlatabadi, J. Rose, and M.G. Morgan, 2001: Climate change and cryptosporidiosis: a qualitative analysis. *Climatic Change,* **50,** 219-249.

CDC, 2004a: Rapid assessment of the needs and health status of older adults after Hurricane Charley – Charlotte, DeSoto, and Hardee Counties, Florida, August 27-31, 2004. *MMWR – Morbidity & Mortality Weekly Report,* **53(36),** 837-840.

CDC, 2004b. *The Impact of Malaria, a Leading Cause of Death Worldwide*. Available at **http://www.cdc.gov/malaria/impact/index.htm**. Page last updated September 13, 2004. Accessed November 12, 2007.

CDC, 2005a: Norovirus outbreak among evacuees from Hurricane Katrina - Houston, Texas, September 2005. *MMWR – Morbidity & Mortality Weekly Report,* **54(40),** 1016-1018.

CDC, 2005b: Heat-related mortality – Arizona, 1993-2002, and United States, 1979-2002. *MMWR – Morbidity & Mortality Weekly Report,* **54(25),** 628-630.

CDC, 2006b: Morbidity surveillance after Hurricane Katrina – Arkansas, Louisiana, Mississippi, and Texas, September 2005. *MMWR – Morbidity & Mortality Weekly Report,* **55(26),** 727-731.

CDC, 2006c: Carbon monoxide poisonings after two major hurricanes - Alabama and Texas, August-October 2005. *MMWR – Morbidity & Mortality Weekly Report,* **55(09),** 236-239.

CDC, 2006d: Mortality Associated with Hurricane Katrina – Florida and Alabama, August-October 2005. *MMWR – Morbidity & Mortality Weekly Report,* **55(09),** 239-242.

Cefalu, W.T., *et al.*, 2006: The Hurricane Katrina aftermath and its impact on diabetes care. *Diabetes Care,* **29(1),** 158-160.

Charles, M.D., R.C. Holman, A.T. Curns, U.D. Parashar, R.I. Glass, and J.S. Breeze, 2006: Hospitalizations associated with rotavirus gastroenteritis in the United States, 1993-2002. *The Pediatric Infectious Disease Journal*, **25(6),** 489-493.

Choi, K.M., G. Christakos, and M.L. Wilson, 2006: El Nino effects on influenza mortality risks in the state of California. *Public Health*, **120(6),** 505-516.

Civerolo, K., C. Hogrefe, C. Rosenzweig, *et al.*, 2006: Estimating the effects of increased urbanization on future surface meteorology and ozone concentrations in the New York City metropolitan region. *Atmospheric Environment*, **41(9),** 1803-1818.

CLIMB, 2004: *Infrastructure Systems, Services and Climate Change: Integrated Impacts and Response Strategies for the Boston Metropolitan Area.* Boston: National Environmental Trust. [Accessed 25 February 2007].

Cook, D.W., 1994: Effect of time and temperature on multiplication of *Vibrio vulnificus* in post-harvest Gulf Coast shellstock oysters. *Applied and Environmental Microbiology*, **60(9)**, 3483-3484.

Cook, S.M., R.I. Glass, C.W. LeBaron, and M.S. Ho, 1990: Global seasonality of rotavirus infections. *Bulletin of the World Health Organization*, **58(2),** 171-177.

Cook, J.T. and D.A. Frank, 2007: Food security, poverty, and human development in the United States. *Annals of the New York Academy of Science*s, 1-16.

Curriero, F.C., J.A. Patz, J.B. Rose, and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American Journal of Public Health*, **91(8),** 1194-1199.

Curriero, F.C., K.S. Heiner, J.M. Samet, S.L. Zeger, L. Strug, and J.A. Patz, 2002: Temperature and mortality in 11 cities of the eastern United States. *American Journal of Epidemiology*, **155(1),** 80-87.

D'Souza, R.M., N.G. Becker, G. Hall, and K.B.A. Moodie, 2004: Does ambient temperature affect foodborne disease? *Epidemiology*, **15(1),** 86-92.

Davies, C.M., C.M. Ferguson, C. Kaucner, M. Krogh, N. Altavilla, D.A. Deere, and N.J. Ashbolt, 2004: Dispersion and transport of *Cryptosporidium* oocysts from fecal pats under simulated rainfall events. *Applied and Environmental Microbiology*, **70(2)**, 1151-1159.

Davis, R., P. Knappenberger, W. Novicoff, and P. Michaels, 2002: Decadal changes in heat-related human mortality in the eastern United States. *Climate Research*, **22,** 175-184.

Davis, R.E., P.C. Knappenberger, P.J. Michaels, and W.M. Novicoff, 2003a: Changing heat-related mortality in the United States. *Environmental Health Perspectives,* **111(14),** 1712-1718.

Davis, R.E., P.C. Knappenberger, W.M. Novicoff, and P.J. Michaels, 2003b: Decadal changes in summer mortality in U.S. cities. *International Journal of Biometeorology,* **47(3),** 166-175.

Davis, R., P. Knappenberger, P. Michaels, and W. Novicoff, 2004: Seasonality of climate-human mortality relationships in US cities and impacts of climate change. *Climate Research,* **26,** 61-76.

Day, J.C., 1996: *Population Projections of the United States by Age, Sex, Race and Hispanic Origin: 1995-2050.* (Census UsBot, ed.), Current Population Reports P25-1130.

DeGaetano, A.T., 2005: Meteorological effects on adult mosquito (*Culex*) populations in metropolitan New Jersey. *International Journal of Biometeorology,* **49(5),** 345-353.

DeGroot, D.W., G. Havenith, and W.L. Kenney, 2006: Responses to mild cold stress are predicted by different individual characteristics in young and older subjects. *Journal of Applied Physiology,* **101(6),** 1607-1615.

Dessai, S., 2003: Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change. *International Journal of Biometeorology,* **48(1),** 37-44.

Devlin, R.B., W.F. McDonnell, R. Mann, S. Becker, D.E. House, D. Schreinemachers, H.S. Koren, 1991: Exposure of humans to ambient levels of ozone for 6.6 hours causes cellular and biochemical changes in the lung. *American Journal of Respiratory Cell and Molecular Biology,* **4**, 72-81.

Diaz, J., A. Jordan, R. Garcia, C. Lopez, J.C. Alberdi, E. Hernandez*, et al.*, 2002: Heat waves in Madrid 1986-1997: effects on the health of the elderly. *International Archives of Occupational & Environmental Health,* **75(3),** 163-170.

Dietz, V.J. and J.M. Roberts, 2000: National surveillance for infection with *Cryptosporidium parvum*, 1995-1998: what have we learned? *Public Health Reports,* **115,** 358-363.

Dockery, D.W., Pope, C.A. III, Xu, X., *et al.* (1993). An association between air pollution and mortality in six U.S. cities. *N Engl J Med* 329:1753-59.

Dominici F, Peng RD, Bell ML, Pham L, McDermott A, Zeger SL, Samet JM. (2006). Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *JAMA*. Mar 8;295(10):1127-34.

Donaldson, G.C., H. Rintamaki, and S. Nayha, 2001: Outdoor clothing: its relationship to geography, climate, behaviour and cold-related mortality in Europe. *International Journal of Biometeorology*, **45(1),** 45-51.

Dushoff, J., J.B. Plotkin, C. Viboud, D.J. Earn, and L. Simonsen, 2005: Mortality due to influenza in the United States – an annualized regression approach using multiple-cause mortality data. *American Journal of Epidemiology*, **163(2),** 181-187.

Dzuiban, E.J., J.L. Liang, G.F. Craun, V. Hill, P.A. Yu, J. Painter, M.R. Moore, R.L. Calderon, S.L. Roy, and M.J. Beach, 2006: Surveillance for waterborne disease and outbreaks associated with recreational water – United States, 2003 – 2004. *MMWR – Morbidity & Mortality Weekly Report,* **55(12),** 1-31.

Ebi, K.L., K.A. Exuzides, E. Lau, M. Kelsh, and A. Barnston, 2001: Association of normal weather periods and El Nino events with hospitalization for viral pneumonia in females: California, 1983–1998. *American Journal of Public Health*, **91(8),** 1200–1208.

Ebi, K.L., T.J. Tieisberg, L.S. Kalkstein, L. Robinson, and R.F. Weiher, 2004: Heat watch/warning systems save lives. *Bulletin of the American Meteorological Society*, **85(8),** 1067-1073.

Ebi, K.L. and J.K. Schmier, 2005: A stitch in time: improving public health early warning systems for extreme weather events. *Epidemiologic Reviews,* **27,** 115-121.

Ebi, K.L., D.M. Mills, J.B. Smith, and A. Grambsch, 2006a: Climate change and human health impacts in the United States: an update on the results of the U.S. national assessment. *Environmental Health Perspectives,* **114(9),** 1318-1324.

Emberlin, J., M. Detandt, R. Gehrig, S. Jaeger, N. Nolard and A. Rantio-Lehtimaki, 2002: Responses in the start of Betula (birch) pollen seasons to recent changes in spring temperatures across Europe. *International Journal of Biometeorology,* **46**, 159-70.

EPA. 2006. Excessive heat events guidebook. http://www.epa.gov/heatisland/about/pdf/EHEguide_final.pdf EPA-430-B-06-005 [Accessed June 2006].

EPRI, 2005: *Interactions of Climate Change and Air Quality: Research Priorities and New Directions.* Electric Power Research Institute, Program on Technology Innovation, Technical Update 1012169.

Fallico, F, K. Nolte, L. Siciliano, and F. Yip, 2005: Hypothermia-related deaths – United States, 2003-2004. *MMWR – Morbidity & Mortality Weekly Report*, **54(07),** 173-175.

Flahault, A., C. Viboud, K. Pakdaman, P.Y. Boelle, M.L. Wilson, M. Myers, and A.J. Valleron, 2004: Association of influenza epidemics in France and the USA with global climate variability. IN: *Proceedings of the International Conference on Options for the Control of Influenza V* [Kawaoka. Y. (ed.)]. Elsevier Inc., San Diego, CA. pp. 73–77.

Fleury, M., D.F. Charron, J.D. Holt, O.B. Allen, and A.R. Maarouf, 2006: A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. *International Journal of Biometerology*, **60,** 385-391.

Folinsbee, L.J., W.F. McDonnell, D.H. Horstman, 1988: Pulmonary function and symptom responses after 6.6-hour exposure to 0.12 ppm ozone with moderate exercise. *Journal of the Air Pollution Control Association*, **38**, 28-35.

Fong, T.T., D.W. Griffin, and E.K. Lipp, 2005: Molecular assays for targeting human and bovine enteric viruses in coastal waters and application for library-independent source tracking. *Applied and Environmental Microbiology*, **71 (4),** 2070-2078.

Ford, E.S., *et al.*, 2006: Chronic disease in health emergencies: in the eye of the hurricane. *Preventing Chronic Disease,* **3(2),** 1-7.

Forkel, R., and R. Knoche, 2006: Regional climate change and its impact on photooxidant concentrations in southern Germany: Simulations with a coupled regional climate-chemistry model. *Journal of Geophysical Research*, **111**.

Fried, J. S., M. S. Torn, and E. Mills. 2004. The impact of climate change on wildfire severity: a regional forecast for northern California. *Climatic Change* **64**:169-191.

Fried, B.J., M.E. Domino, and J. Shadle, 2005: Use of mental health services after hurricane Floyd in North Carolina. *Psychiatric Services,* **56(11),** 1367-1373.

Frost, F.J., T.R. Kunde, and G. F. Craun, 2002: Is contaminated groundwater an important cause of viral gastroenteritis in the United States? *Journal of Environmental Quality*, **65(3)**, 9-14.

Furness, B.W., M.J. Beach, and J.M. Roberts, 2000: Giardiasis surveillance – United States, 1992-1997. *MMWR – Morbidity & Mortality Weekly Report*, **49(07),** 1-13.

Gangarosa, R.E., R.I. Glass, J.F. Lew, and J.R. Boring, 1992: Hospitalizations involving gastroenteritis in the United States, 1985: The special burden of the disease among the elderly. *American Journal of Epidemiology,* **135(3),** 281-290.

Gatntzer, C., E. Dubois, J,-M. Crance, S. Billaudel, H. Kopecka, L. Schwartzbrod, M. Pommepuy, and F. Le Guyader, 1998: Influence of environmental factors on survival of enteric viruses in seawater. *Oceanologica Acta*, **21(6)**, 883-992.

Gedalof, Z., D.L. Peterson, and N.J. Mantua, 2005: Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *Ecological Applications,* **15(1),** 154-174.

Gerrity, E.T., and B.W. Flynn, 1997: Mental health consequences of disasters. IN: *The Public Health Consequences of Disasters* [Noji. E.K. (ed.)]. Oxford University Press, New York, NY. pp. 101–121.

Goodman, R.A., J.W. Buehler, H.B. Greenberg, T.W. McKinley, and J.D. Smith, 1982: Norwalk gastroenteritis associated with a water system in a rural Georgia community. *Archives of Environmental Health,* **37(6)**, 358-360.

Goodman, P.G., D.W. Dockery, and L. Clancy, 2004: Cause-specific mortality and the extended effects of particulate pollution and temperature exposure. [erratum appears in Environ Health Perspect. 2004 Sep; 112(13), A729]. *Environmental Health Perspectives,* **112(2),** 179-185.

Gouveia, N., S. Hajat, and B. Armstrong, 2003: Socio-economic differentials in the temperature-mortality relationship in Sao Paulo, Brazil. *International Journal of Epidemiology,* **32,** 390-397.

Greenberg, J.H., J. Bromberg, C.M. Reed, T.L. Gustafson, R.A. Beauchamp, 1983: The epidemiology of heat-related deaths, Texas – 1950, 1970-79, and 1980. *American Journal of Public Health,* **73(7),** 805-807.

Greene, S.K., E.L. Ionides, and M.L. Wilson, 2006: Patterns of influenza-associated mortality among US elderly by geographic region and virus subtype, 1968-1998. *American Journal of Epidemiology,* **163(4),** 316-326.

Greenough G, McGeehin M, Bernard SM, Trtanj J, Riad J, Engleberg D. 2001. The potential impacts of climate variability and change on health impacts of extreme weather events in the United States. *Environmental Health Perspectives* 109 Suppl:191-8.

Griffin, K., A. Donaldson, J.H. Paul, and J.B. Rose, 2003: Pathogenic human viruses in coastal waters. *Clinical Microbiology Reviews*, **16(1)**, 129-143.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, and J.H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. *Journal of Hydrometeorology,* **5,** 64-85.

Gubler, D.J., P. Reiter P., K.L. Ebi, W. Yap, R. Nasci, and J.A. Patz, 2001: Climate variability and change in the United States: potential impacts on vector- and rodent-borne diseases. *Environmental Health Perspectives*, **109(2),** 223-233.

Guzmán, M.G. and G. Kourí, 2002: Dengue: an update. *Lancet Infect Dis*. **2(1)**, 33-42. Review.

Haines, A., R.S. Kovats, D. Campbell-Lendrum, and C. Corvalan, 2006a: Climate change and human health: impacts, vulnerability, and public health. *Lancet*, **367(9528),** 2101-2109.

Haines, A., R.S. Kovats, D. Campbell-Lendrum, and C. Corvalan, 2006b: Climate change and human health: impacts, vulnerability and public health. *Public Health*, **120(7)**, 585-596.

Hajat, S., *et al.*, 2003: The health consequences of flooding in Europe and the implications for public health: A Review of the Evidence. *Applied Environmental Science and Public Health,* **1(1),** 13-21.

Hajat, S., R. Kovats, and K. Lachowycz, 2007: Heat-related and cold-related deaths in England and Wales: who is at risk? *Occupational Environmental Medicine,* **64,** 93-100.

Haley, B.J., 2006: Ecology of *Salmonella* in a Southeastern Watershed. University of Georgia, M.S. Thesis. Athens, GA.

Halverson, J.B., 2006: A climate conundrum: the 2005 hurricane season has been touted as proof of global warming and an indication of worse calamities to come. Where is the line between fact and speculation? *Weatherwise,* **(March/April),** 19-23.

Havenith, G., Y. Inoue, V. Luttikholt, and W.L. Kenney, 1995: Age predicts cardiovascular, but not thermoregulatory, responses to humid heat stress. *European Journal of Applied Physiology & Occupational Physiology,* **70(1),** 88-96.

Havenith, G., J.M. Coenen, L. Kistemaker, and W.L. Kenney, 1998: Relevance of individual characteristics for human heat stress response is dependent on exercise intensity and climate type. *European Journal of Applied Physiology & Occupational Physiology,* **77(3),** 231-241.

Havenith, G., 2001: Individualized model of human thermoregulation for the simulation of heat stress response. *Journal of Applied Physiology,* **90(5),** 1943-1954.

Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, *et al.*, 2004: Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences of the United States of America*, **101(34),** 12422-12427.

Healy, J.D., 2003: Excess winter mortality in Europe: a cross country analysis identifying key risk factors. *Journal of Epidemiology and Community Health,* **57(10),** 784-789.

Herikstad, H., S. Yang, T.J. Van Gilder, D. Vugia, J. Hadler, P. Blake, V. Deneen, B. Shiferaw, F.J. Angulo and the Foodnet Working Group, 2002: A population-based estimate of the burden of diarrhoeal illness in the United States: FoodNet, 1996-7. *Epidemiology and Infection*, **19**, 9-17.

Hogrefe, C., J. Biswas, B. Lynn, K. Civerolo, J-Y. Ku, J. Rosenthal, C. Rosenzweig, R. Goldberg, and P.L. Kinney, 2004a: Simulating regional-scale ozone climatology over the Eastern United States: Model evaluation results, *Atmospheric Environment*, **38,** 2627-2638.

Hogrefe, C., K. Civerolo, J-Y. Ku, B. Lynn, J. Rosenthal, K. Knowlton, B. Solecki, C. Small, S. Gaffin, R. Goldberg, C. Rosenzweig, and P.L. Kinney, 2004b: *Modeling the Air Quality Impacts of Climate and Land Use Change in the New York City Metropolitan Area.* Models-3 Users' Workshop, October 18-20, Research Triangle Park, NC, USA. Available online: http://www.cmascenter.org/html/2004_workshop/abstracts/Climate%20Multiscale/Hogrefe_abstract.pdf

Hogrefe, C., B. Lynn, K. Civerolo, J-Y. Ku, J. Rosenthal, C. Rosenzweig, *et al.*, 2004c: Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. *Journal of Geophysical Research*, **109,** D22301.

Hogrefe, C., R. Leung, L. Mickley, S. Hunt, and D. Winner, 2005a: Considering climate change in air quality management. *Environmental Manager (EM)*, 19-23.

Hogrefe, C., B. Lynn, C. Rosenzweig, R. Goldberg, K. Civerolo, J-Y. Ku, J. Rosenthal, K. Knowlton, and P.L. Kinney, 2005b: *Utilizing CMAQ Process Analysis to Understand the Impacts of Climate Change on Ozone and Particulate Matter.* Models-3 Users' Workshop, September 26-28, Chapel Hill, NC, USA. Available online: http://www.cmascenter.org/html/2005_conference/abstracts/3_2.pdf.

Hogrefe, C., K. Civerolo, J-Y. Ku, B. Lynn, J. Rosenthal, B. Solecki, C. Small, S. Gaffin, K. Knowlton, R. Goldberg, C. Rosenzweig, and P.L. Kinney, 2006: Air quality in future decades – determining the relative impacts of changes in climate, anthropogenic and biogenic emissions, global atmospheric composition, and regional land use. In: *Air Pollution Modeling and its Application XVII* [Borrego, C. and A.L. Norman (eds.)]. Proceedings of the 27^{th} NATO/CCMS International Technical Meeting on Air Pollution Modeling and its Application, October 25-29, 2004, Banff, Canada. Springer, 772 pp.

Holley, K., M. Arrus, K.H. Ominiski, M. Tenuta, and G. Blank, 2006: *Salmonella* survival in manure-treated soils during simulated seasonal temperature exposure. *Journal of Environmental Quality*, **35**, 1170-1180.

Howell, D. and D. Cole, 2006: Leptospirosis: a waterborne zoonotic disease of global importance. *Georgia Epidemiology Report*, **22(8),** 1-2.

Hrudey, S.E., P. Payment, P.M. Houck, R.W. Gillham, and E.J. Hrudry, 2003: A fatal waterborne disease epidemic in Walkerton, Ontario: comparison with other waterborne outbreaks in the developed world. *Water Science and Technology*, **47(3),** 7-14.

Huynen, M., and B. Menne, 2003: Phenology and human health: allergic disorders. *Report of a WHO meeting in Rome, Italy, 16-17 January 2003*. *Health and Global Environmental Series*. EUR/03/5036791, World Health Organization, Copenhagen, 64 pp

IPCC, 2007a: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC, 2007b: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

Jacobson M.Z., 2008: On the causal link between carbon dioxide and air pollution mortality. *Geophysical Research Letter*s, **35**, L03809. doi:10.1029/2007GL031101

Jamieson, D.J., *et al.*, 2006: Emerging infections and pregnancy. *Emerging Infectious Diseases*, **12(11),** 1638-1643.

Janda, J.M., C. Powers, R.G. Bryant, and S.L. Abbott, 1988: Clinical perspectives on the epidemiology and pathogenesis of clinically significant *Vibrio* spp. *Clinical Microbiology Reviews*, **1(3),** 245-267.

Jones, T.S., A.P. Liang, E.M. Kilbourne, M.R. Griffin, P.A. Patriarca, S.G. Wassilak, *et al.*, 1982: Morbidity and mortality associated with the July 1980 heat wave in St Louis and Kansas City, Mo. *Journal of the American Medical Association*, **247(24),** 3327-3331.

Kalkstein, L.S. 1993: Health and Climate Change: Direct Impacts in Cities. *Lancet*, **342,** 1397-1399.

Kalkstein, L.S., 2000: Saving lives during extreme weather in summer. *British Medical Journal*, **321(7262),** 650-651.

Katz, A.R., V.E. Ansdell, P.V. Effler, C.R. Middleton, and D.M. Sasaki, 2002: Leptospirosis in Hawaii, 1974-1988: epidemiologic analysis of 353 laboratory-confirmed cases. *American Journal of Tropical Medicine and Hygiene*, **66(1),** 61-70.

Keatinge, W.R. and G.C. Donaldson, 2001: Mortality related to cold and air pollution in London after allowance for effects of associated weather patterns. *Environmental Research,* **86(3),** 209-216.

Khetsuriani, N., A. LaMonte-Fowlkes, M.S. Oberste, and M.A. Pallansch, 2006: Enterovirus surveillance – United States, 1970 – 2005. *MMWR – Morbidity & Mortality Weekly Reports,* **55(08),** 1-20.

Khosla, R. and K.K. Guntupalli, 1999. Heat-related illnesses. [Review] [32 refs]. *Critical Care Clinics,* **15(2),** 251-263.

Kim, J., 2003: Effects of climate change on extreme precipitation events in the western US. In: *AMS Symposium on Global Change and Climate Variations, V. 14.* American Meteorological Society, Boston, MA.

King, B.J. and P.T. Monis, 2006: Critical processes affecting *Cryptosporidium* oocyst survival in the environment. *Parasitology,* 1-15.

Kinney, P.L., and Ozkaynak, H., 1991: Associations of daily mortality and air pollution in Los Angeles County. *Environ. Res.* **54**:99-120.

Kinney, P.L., C. Rosenzweig, C. Hogrefe, *et al.*, 2006: Chapter 6. Assessing the Potential Public Health Impacts of Changing Climate and Land Use: NY Climate & Health Project. In: *Climate Change and Variability: Impacts and Responses* [Ruth M., K. Donaghy K, and P. Kirshen (eds.)]. New Horizons in Regional Science, Edward Elgar, Cheltenham, UK.

Kistemann T, Classen T, Koch C, Dangendorf F, Fischeder R, Gebel J, Vacata V, Exner M. 2002. Microbial load of drinking water reservoir tributaries during extreme rainfall and runoff. *Appl Environ Microbiol* 68:2188-97.

Klinenberg, E., 2002: *Heat Wave: A Social Autopsy of Disaster in Chicago.* The University of Chicago Press, Chicago.

Knowlton, K., J. Rosenthal, C. Hogrefe, B. Lynn, S. Gaffin, R. Goldberg, C. Rosenzweig, K. Civerolo, J-Y. Ku, P.L. Kinney, 2004: Assessing ozone-related health impacts under a changing climate. *Environmental Health Perspectives,* **112**:1,557–1,563.

Knowlton, K., B. Lynn, R. Goldberg, C. Rosenzweig, C. Hogrefe, J. Rosenthal, *et al.*, 2007: Projecting heat-related mortality impacts under a changing climate in the New York City region. *American Journal of Public Health*, **97**(11) 2028-34.

Kolivras, K.N. and A.C. Comrie, 2003: Modeling valley fever (coccidioidomycosis) incidence on the basis of climate conditions. *International Journal of Biometeorology* **47**, 87-101.

Kosatsky, T., M. Baccini, A. Biggeri, G. Accetta, B. Armstrong, B. Menne, *et al.*, 2006: Years of life lost due to summertime heat in 16 European cities. *Epidemiology* **17(6),** 85.

Kovats, R.S., S.J. Edwards, S. Hajat, B. Armstrong, K.L. Ebi, B. Menne, and The Collaborating Group, 2004a: The effect of temperature on food poisoning: a time-series analysis of salmonellosis in ten European countries. *Epidemiology and Infection*, **132,** 443-453.

Kovats, R.S., S. Hajat S, and P. Wilkinson, 2004b: Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. *Occupational & Environmental Medicine,* **61(11),** 893-898.

Kovats, R.S., S.J. Edwards, D. Charron, J. Cowden, R.M. D'Souza, K.L. Ebi, C. Gauci, P.G Smidt, S. Hajat, S. Hales, G.H. Pezzi, B. Kriz, K. Kutsar, P. McKeown, K. Mellou, B. Menne, S. O'Brien, W. van Pelt, and H. Schmidt, 2005b: Climate variability and campylobacter infection: an international study. *International Journal of Biometerology*, **49,** 207-214.

Kovats, R.S. and K.L. Ebi, 2006: Heatwaves and public health in Europe. *European Journal of Public Health*, **16(6),** 592-599.

Kunkel, K.E., 2003: North American trends in extreme precipitation. *Natural Hazards,* **29,** 291-305.

Kunkel, K.E., R.J. Novak, R.L. Lampman, and W. Gu, 2006: Modeling the impact of variable climatic factors on the crossover of *Culex restauns* and *Culex pipiens* (Diptera: Culicidae), vectors of West Nile virus in Illinois. *American Journal of Tropical Medicine & Hygiene*, 168-173.

Künzli, N., M. Jerrett, W.J. Mack, B. Beckerman, L. LaBree, F. Gilliland, D. Thomas, J. Peters, and H.N. Hodis, 2005. Ambient air pollution and atherosclerosis in Los Angeles. Environmental Health Perspectives, **113**, 201-206.

Lacy, R.W., 1993: Foodborne bacterial infections. *Parasitology*, **107 Suppl**, S75-S93.

Landsea, C. W., 2005: Hurricanes and global warming. *Nature* **438:**11-12.

Lachowsky, K. and R. Kovats, 2006: Estimating the burden of disease due to heat and cold under current and future climates. *Epidemiology,* **17(6),** S50.

Laden, F., Schwartz, J., Speizer, F.E., Dockery, D.W. (2006). Reduction in fine particulate air pollution and mortality: extended. Am J Respir Crit Care Med 173:667-72.

Lee, S.H., D.A. Levy, G.F. Craun, M.J. Beach, and R.L. Calderon, 2002: Surveillance for waterborne disease outbreaks – United States, 1999 – 2000. *MMWR – Morbidity & Mortality Weekly Report*, **51(08),** 1-28.

Leung, R.L. and W.I. Gustafson Jr., 2005: Potential regional climate change and implications to U.S. air quality. *Geophysical Research Letters*, **32(16)**.

Liang, J.I., E.J. Dziuban, G.F. Craun, V. Hill, M.R. Moore, R.J. Gelting, R.L. Calderon, M.J. Beach, and S.L. Roy, 2006: Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking – United States, 2003 – 2004. *MMWR – Morbidity & Mortality Weekly Report*, **55(12),** 32-65.

Lindgren, E., L. Talleklint, and T. Polfeldt, 2000: Impact of climatic change on the northern latitude limit and population density of the disease-transmitting European tick *Ixodes ricinus*. *Environmental Health Perspectives*, **108(2),** 119-123.

Lipp, E.K. and J.B. Rose, 1997: The role of seafood in foodborne diseases in the United States of America. *Revue Scientifique et Technique (Office International des Epizooties)*, **16(2),** 620-640.

Lipp, E.K., R. Kurz, R. Vincent, C. Rodriguez-Palacios, S.R. Farrah, and J.B. Rose, 2001a: The effects of seasonal variability and weather on microbial fecal pollution and enteric pathogens in a subtropical estuary. *Estuaries,* **24(2),** 266-276.

Lipp, E.K., C. Rodriguez-Palacios, and J.B. Rose, 2001b: Occurrence and distribution of the human pathogen *Vibrio vulnificus* in a subtropical Gulf of Mexico estuary. *Hydrobiologia,* **460,** 165-173.

Lipp, E.K., A. Huq, and R.R. Colwell, 2002: Effects of global climate in infectious disease: the cholera model. *Clinical Microbiology Reviews*, **15(4),** 757-770.

Lobitz, B., L. Beck, A. Huq, B. Wood, G. Fuchs, A.S.G. Faruque and R. Colwell, 2000: Climate and infectious disease: use of remote sensing for detection of *Vibrio cholerae* by indirect measurement. *Proceedings of the National Academy of Sciences*, **97**, 1438-1443.

Louis, V.R., I.A. Gillespie, S.J. O'Brien, E. Russek-Cohen, A.D. Pearson, and R.R. Colwell, 2005: Temperature-driven campylobacter seasonality in England and Wales. *Applied and Environmental Microbiology,* **71(1),** 85-92.

Louis VR, Russek-Choen E, Choopun N, Rivera IN, Gangle B, Jiang SC, Rubin A, Patz JA, Hug A, Colwell RR. 2003. Predictability of Vibrio cholerae in Chesapeake Bay. *Appl Environ Microbiol* 69:2773-85.

Louisiana Department of Health and Hospitals (LDHH), 2006: *Vital Statistics of All Bodies at St. Gabriel Morgue.* 23 February 2006.

Lynch, M., J. Painter, R. Woodruff, and C. Braden, 2006: Surveillance for foodborne-disease outbreaks – United States, 1998-2002. *MMWR – Morbidity & Mortality Weekly Reports*, **55(10),** 1-42.

Marciano-Cabral, F., R. MacLean, A. Mensah, and L. LaPat-Polasko, 2003: Identification of *Naegleria fowleri* in domestic water sources by nested PCR. *Applied and Environmental Microbiology,* **69(10),** 5864-5869.

McCabe, G.J. and J.E. Bunnell, 2004: Precipitation and the occurrence of Lyme disease in the northeastern United States. *Vector Borne & Zoonotic Diseases,* **4(2),** 143-148.

McConnell, R., K. Berhane, F. Gilliland, S.J. London, T. Islam, *et al.* 2002: Asthma in exercising children exposed to ozone: a cohort study. *Lancet*, **359**:386-391.

McGeehin, M.A. and M. Mirabelli, 2001: The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environmental Health Perspectives*, **109(2),** 185-189.

McLaughlin, J.B., A. DePaola, C.A. Bopp, K.A. Martinek, N.P. Napolilli, C.G.Allison, S.L. Murray, E.C. Thompson, M.M. Bird, and J.P. Middaugh, 2005: Outbreaks of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *New England Journal of Medicine,* **353(14),** 1463-1470.

Mead, P.S., L. Slutsker, V. Dietz, L.F. McCaig, J.S. Bresee, C. Shapiro, P.M. Griffin, and R.V. Tauxe, 1999: Food-related illness and death in the United States. *Emerging Infectious Diseases,* **5(5),** 607-625.

Medina-Ramon, M., A. Zanobetti, D.P. Cavanagh, and J. Schwartz, 2006: Extreme temperatures and mortality: assessing effect modification by personal characteristics and specific cause of death in a multi-city case-only analysis. *Environmental Health Perspectives,* **114(9),** 1331-1336.

Meehl, G.A. and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science,* **305(5686),** 994-997.

Meites, E., M.T. Jay, S. Deresinski, W.J. Shieh, S.R. Zaki, L. Tomkins, and D.S. Smith, 2004: Reemerging leptospirosis, California. *Emerging Infectious Diseases,* **10(3),** 406-412.

Mickley, L.J., D.J. Jacob, B.D. Field, and D. Rind, 2004: Effects of future climate change on regional air pollution episodes in the United States. *Geophysical Research Letters,* **31,** L24103.

Middleton, K.L., J. Willner, and K. M. Simmons, 2002: Natural disasters and posttraumatic stress disoder symptom complex: evidence from the Oklahoma tornado outbreak. *International Journal of Stress Management*, **9(3),** 229-236.

Miossec, L., F. Le Guyader, L. Haugarreau, and M. Pommepuy, 2000: Magnitude of rainfall on viral contamination of the marine environment during gastroenteritis epidemics in human coastal population. *Revue Epidemiologie Sante Publique*, **38(suppl 2)**, 62-71.

Mississippi Department of Health (MSDH), 2005: *Mississippi Vital Statistics 2005.* 14 February 2007.

Mohan, J.E., L.H. Ziska, W.H. Schlesinger, R.B. Thomas, R.C. Sicher, K. George and J.S. Clark, 2006: Biomass and toxicity responses of poison ivy (Toxicodendron radicans) to elevated atmospheric CO_2. *Proceedings of the National Academy of Sciences*, **103**, 9086-9089.

Morris, J.G., 2003: Cholera and other types of vibriosis: a story of human pandemics and oysters on the half shell. *Clinical Infectious Diseases,* **37,** 272-280.

Mounts, A.W., T. Ando, M. Koopmans, J.S. Breese, J. Noel and R.I. Glass, 2000: Cold weather seasonality of gastroenteritis associated with Norwalk-like Viruses. *Journal of Infectious Diseases*, **181(Suppl 2)**, S284-S287.

Mouslin C, Hilber F, Huang H, Groisman FA. 2002. Conflicting needs for a Salmonella hypervirulence gene in host and non-host environments. *Mol Microbiol* 45:1019-27.

Murazaki, K., and P. Hess, 2006: How does climate change contribute to surface ozone change over the United States? *Journal of Geophysical Research,* **111**.

NAS Committee on Climate Ecosystems Infectious Disease and Human Health Board on Atmospheric Sciences and Climate and National Research Council (NRC), 2001: *Under the Weather: Climate, Ecosystems, and Infectious Disease.* Washington: National Academics Press.

Naumova, E.N., J.S. Jjagai, B. Matyas, A. DeMaria, I.B. MacNeill, and J.K. Griffiths, 2006: Seasonality in six enterically transmitted diseases and ambient temperature. *Epidemiology and Infection*, 1-12.

New England Governors and Eastern Canadian Premiers (NEC/ECP), 2001: *Report to New England Governors and Eastern Canadian Premiers Climate Change Action Plan.* New England Governor's Conference Inc., Boston , MA. Available at: http://www.negc.org/documents/NEG-ECP%20CCAP.pdf [Accessed 12 February 2007].

Newel, D. G,. 2002: The ecology of *Campylobacter jejuni* in avian and human hosts and in the environment. *International Journal of Infectious Diseases*, **6,** 16-21.

NOAA, 2005a: *65-Year List of Severe Weather Fatalities.* http://www.weather.gov/os/severe_weather/65yrstats.pdf. [Accessed 23 February 2007].

NOAA, 2005b: *NOAA Heat/Health Watch Warning System Improving Forecasts and Warnings for Excessive Heat.* NOAA Air Resources Laboratory. Available: http://www.arl.noaa.gov/ss/transport/archives.html [accessed March 4, 2005 2005].

NOAA, 2006: *Galveston Storm of 1900.* http://www.noaa.gov/galveston1900 [Accessed 23 February 2007].

NOAA, 2007a. 67-Year List of Severe Weather Fatalities. http://www.weather.gov/om/hazstats.shtml. Accessed October 18, 2007.

NOAA, 2007b. Billion dollar climate and weather disasters 1980-2006. www.ncdc.noaa.gov/oa/reports/billionz.html. Accessed January 31, 2007.

NOAA, 2007c. Climate Models Suggest Warming-Induced Wind Shear Changes Could Impact Hurricane Development Intensity. www.noaanews.noaa.gov/stroies2007/s2840.htm.

North, C.S., A. Kawasaki, E.L. Spitznagel, and B.A. Hong, 2004: The course of PTSD, major depression, substance abuse, and somatization after a natural disaster. *The Journal of Nervous and Mental Disease*, **192(12),** 823-829.

Ogden, N.H., A. Maarouf, I.K. Barker, M. Bigras-Poulin, L.R. Lindsay, M.G. Morshed, C.J. O'Callaghan, F. Ramay, D. Waltner-Toews, and D.F. Charron, 2006: Climate change and the potential for range expansion of the Lyme disease vector *Ixodes scapularis* in Canada. *International Journal for Parasitology*, **36(1),** 63-70.

O'Neill, M.S., *et al.*, 2003a: Health, wealth, and air pollution: advancing theory and methods. *Environmental Health Perspectives,* **111(16),** 1861-1870.

O'Neill, M.S., A. Zanobetti, and J. Schwartz, 2003b: Modifiers of the temperature and mortality association in seven US cities. *American Journal of Epidemiology,* **157(12),** 1074-1082.

O'Neill M.S. 2003c: Air conditioning and heat-related health effects. *Applied Environmental Science and Public Health* 2003;**1(1):**9-12.

O'Neill, M., S. Hajat, A. Zanobetti, M. Ramirez-Aguilar, and J. Schwartz, 2005a: Impact of control for air pollution and respiratory epidemics on the estimated associations of temperature and daily mortality. *International Journal of Biometeorology*.

O'Neill M.S., Zanobetti A, Schwartz J. 2005b: Disparities by race in heat-related mortality in four U.S. cities: the role of air conditioning prevalence. *Journal of Urban Health* 2005;82(2):191-197.

Ostfeld, R.S., C.D Canham, K. Oggenfuss, R.J. Winchcombe, and F. Keesing, 2006: Climate, deer, rodents, and acorns as determinants of variation in Lyme disease risk. *PLoS Biology,* **4(6),** e145.

Parkinson AJ, Butler JC. 2005. Potential impacts of climate change on infectious diseases in the Arctic. *Int J Circumpolar Health* 64:478-86.

Parry, M., C. Rosenzweig, and M. Livermore, 2005: Climate change, global food supply and risk of hunger. *Philosophical Transactions of the Royal Society B,* 360, 2125-2138.

Patz JA, McGeehin MA, Bernard SM, Ebi KL, Epstein PR, Grambsch A, Gubler DJ, Reiter P, Romieu I, Rose JB, Samet JM, Trtanj J. 2000. The potential health impacts of climate variability and change for the United States: executive summary of the report of the health sector of the U.S. National Assessment. *Environmental Health Perspectives* 108:367-76.

Pfeffer, C.S., M.F. Hite, and J.D. Oliver, 2003: Ecology of *Vibrio vulnificus* in estuarine waters of eastern North Carolina. *Applied and Environmental Microbiology,* **69(6),** 3526-3531.

Piacentino, J.D. and B.S. Schwartz, 2002: Occupational risk of lyme disease: an epidemiological review. *Occupational and Environmental Medicine,* **59,** 75-84

Pielke, Jr., R.A., C. Landsea, M. Mayfield, J. Laver, and R. Pasch, 2005: Hurricanes and global warming. *Bulletin of the American Meteorological Society,* 1571-1575.

Pinho, O.S. and M.D. Orgaz, 2000: The urban heat island in a small city in coastal Portugal. *International Journal of Biometeorology,* **44(4),** 198-203.

Pope, C.A., III, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, and G.D. Thurston, 2002: Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. J*AMA,* **287,** 1132-1141.

Pope, C.A. III, Thun, M., Namboodiri, M., *et al.* (1995). Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. Am J Respir Crit Care Med 151:669-74.

Pope, C.A. III , Burnett, R.T., Thurston, G.D., Thun, M.J., Calle, E.E., Krewski, D., Godleski, J.J. (2004). Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. Circulation. 109(1):71-7.

Pope CA, Dockery DW. Health effects of fine particulate air pollution: Lines that connect. J Air and Waste Management Association. 2006; 54: 709-742.

Powell, D. and B. Chapman, 2007: Fresh threat: what's lurking in your salad bowl? *Journal of the Science of Food and Agriculture*, **87**, 1799-1801.

Purse, B.V., P.S. Mellor, D.J. Rogers, A.R. Samuel, P.P. Mertens, and M. Baylis, 2005: Climate change and the recent emergence of bluetongue in Europe. *Nature Reviews Microbiology,* **3(2),** 171-181.

Randa, M.A., M.F. Polz, and E. Lim, 2004: Effects of temperature and salinity on *Vibrio vulnificus* population dynamics as assessed by quantitative PCR. *Applied and Environmental Microbiology*, **70(9),** 5469-5476.

Randolph, S.E. and D.J. Rogers, 2000: Fragile transmission cycles of tick-borne encephalitis virus may be disrupted by predicted climate change. *Proceedings Biological Sciences/The Royal Society*, **267(1454),** 1741-1744.

Randolph, S.E., 2004a: Evidence that climate change has caused 'emergence' of tick-borne diseases in Europe? *International Journal of Medical Microbiology,* **293(37),** 5-15.

Reisen, W.K., Y. Fang, and V.M. Martinez , 2006: Effects of temperature on the transmission of West Nile virus by Culex tarsalis (Diptera: Culicidae). *Journal of Medical Entomology*, **43(2)**:309-17.

Reiter, P. 1996. Global warming and mosquito-borne disease in USA. *Lancet* 348:622

Reiter, P., S. Lathrop, M. Bunning, B. Biggerstaff B., D Singer, T Tiwari, L. Baber M. Amador, J. Thirion, J. Hayes, C. Seca, J. Mendez, B. Ramirez, J. Robinson, J. Rawlings, V. Vorndam, S. Waterman, D. Gubler, G Clark and E. Hayes. , 2003. Texas lifestyle limits transmission of dengue virus. *Emerging Infectious Diseases*. **9(1),** 86-89.

Ren, C., G.M. Williams, and S. Tong, 2006: Does particulate matter modify the association between temperature and cardiorespiratory diseases? *Environmental Health Perspectives*, **114(11),** 1690-1696.

Rogers, C., P. Wayne, E. Macklin, M. Muilenberg, C. Wagner, P. Epstein and F. Bazzaz, 2006: Interaction of the onset of spring and elevated atmospheric CO2 on ragweed (Ambrosia artemisiifolia L.) pollen production. *Environmental Health Perspectives*, **114** (6), 865-869. doi:10.1289/ehp.8549.

Rose, J.B., S. Daeschner, D.R. Easterling, F.C. Curriero, S. Lele, and J.A. Patz, 2000: Climate and waterborne disease outbreaks. *Journal of the American Water Works Association,* **92(9),** 77-87.

Running, S.W., 2006: Is global warming causing more, larger wildfires? *Science,* **313,** 927-928.

Russoniello, C.V., T.K. Skalko, K. O'Brien, S.A. McGhee, D. Bingham-Alexander, and J. Beatley, 2002: Childhood posttraumatic stress disorder and efforts to cope after hurricane Floyd. *Behavioral Medicine,* **28,** 61-71.

Rzezutka, A., and N. Cook, 2004: Survival of human enteric viruses in the environment and food. *FEMS Microbiology Reviews,* **28**, 441-453.

Samet, J.M., F. Domenici, F. Curriero, I. Coursac, and S.L. Zeger, 2000: Fine Particulate Air Pollution and Mortality in 20 U.S. Cities, 1987–1994. *New England Journal of Medicne,* **343,** 1742-1749.

Schwartz, B.S. and M.D. Goldstein MD, 1990: Lyme disease in outdoor workers: risk factors, preventive measures, and tick removal methods. *American Journal of Epidemiology,* **131(5),** 877-885.

Schwartz, J., 1995: Short term fluctuations in air pollution and hospital admissions of the elderly for respiratory disease. *Thorax* **50**, 531–538

Schwartz, J., J.M. Samet, and J.A. Patz, 2004: Hospital admissions for heart disease: The effects of temperature and humidity. *Epidemiology,* **15(6),** 755-761.

Schwartz, J., 2005: Who is sensitive to extremes of temperature? A case-only analysis. *Epidemiology,* **16(1),** 67-72.

Seidell, J.C., 2000: Obesity, insulin resistance and diabetes – a worldwide epidemic. *British Journal of Nutrition,* **83(1),** S5-8.

Semenza, J.C., C.H. Rubin, K.H. Falter, J.D. Selanikio, W.D. Flanders, H.L. Howe, *et al.*, 1996: Heat-related deaths during the July 1995 heat wave in Chicago. *New England Journal of Medicine,* **335(2),** 84-90.

Semenza, J.C., J.E. McCullough, W.D. Flanders, M.A. McGeehin, and J.R. Lumpkin, 1999: Excess hospital admissions during the July 1995 heat wave in Chicago. *American Journal of Preventive Medicine*, **16(4),** 269-277.

Senior, C.A., R.G. Jones, J.A. Lowe, C.F. Durman, and D. Hudson, 2002: Predictions of extreme precipitation and sea-level rise under climate change. *Philosophical Transactions of the Royal Society of London*, **360(A),** 1301-1311.

Setzer, C. and M.E. Domino, 2004: Medicaid outpatient utilization for waterborne pathogenic illness following Hurricane Floyd. *Public Health Reports,* **119,** 472-478.

Sheridan, S. and T. Dolney, 2003: Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, USA. *Climate Research,* **24,** 255-266.

Sheridan, S.C., 2006: A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness. *International Journal of Biometeorology*.

Shone, S.M., F.C. Curriero, C.R. Lesser, and G.E. Glass, 2006: Characterizing population dynamics of *Aedes sollicitans* (Diptera: Culicidae) using meteorological data. *Journal of Medical Entomology,* **43(2),** 393-402.

Sibold, J.S. and T.T. Veblen, 2006: Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. *Journal of Biogeography*, **33,** 833-842.

Skelly, C. and P. Weinstein, 2003: Pathogen survival trajectories: an eco-environmental approach to the modeling of human campylobacteriosis ecology. *Environmental Health Perspectives*, **111(1)**, 19-28.

Southern, J.P., R.M. Smith and S.R. Palmer, 1990: Bird attack on milk bottles: possible mode of transmission of *Campylobacter jejuni* to man. *Lancet*, **336**, 1425-1427.

Srikantiah, P, J.C. Lay, S. Hand, J.A. Crump, J. Campbell, M.S. Van Duyne, R. Bishop, R.Middendor, M. Currier and P.S. Mead, 2004: *Salmonella enterica* serotype Javiana infections associated with amphibian contact, Mississippi, 2001. *Epidemiology and Infection*, **132**, 273-281.

Stanley, K.N., J.S. Wallace, J.E. Currie, P.J. Diggle and K. Jones, 1998: The seasonal variation of thermophilic campylobacters in beef cattle, dairy cattle and calves. *Journal of Applied Microbiology*, **85(3)**, 472-480.

Steiner, A.L., S. Tonse, R.C. Cohen, A.H. Goldstein, and R.A. Harley, 2006: Influence of future climate and emissions on regional air quality in California. *Journal of Geophysical Research,* **111**.

Subak, S., 2003: Effects of climate on variability in Lyme disease incidence in the northeastern United States. *American Journal of Epidemiology*, **157(6),** 531–538.

Tapsell, S.M., E.C. Penning-Rowsell, S.M. Tunstall, and T.L. Wilson, 2002: Vulnerability to flooding: health and social dimensions. *Philosophical Transactions of the Royal Society of London A*, 360, 1511-1525.

Thomas, M.K., D.F. Charron, D.Waltner-Toews, C. Schuster, A.R. Maarouf, and J.D. Holt, 2006: A role of high impact weather events in waterborne disease outbreaks in Canada, 1975 – 2001. *International Journal of Environmental Health Research,* **16(3),** 167-180.

Thompson, J.R., M.A. Randa, L.A. Marcelino, A.Tomita-Mitchell, E. Lim, and M.F. Polz, 2004: Diversity and dynamics of a North Atlantic coastal *Vibrio* community. *Applied and Environmental Microbiology,* **70(7),** 4103-4110.

Trenberth, K., 2005: Uncertainty in hurricanes and global warming. *Science,* **308,** 1753-1754.

U.S. Census Bureau. 2004. U.S. Interim Projections by Age, Sex, race, and Hispanic. http://www.census.gov/ipc/www/usinterimproj/. Accessed September 12, 2007.

U.S. EPA, 2005: *Heat island effect.* U.S. Environmental Protection Agency. [Accessed 11 February 2005].

U.S. EPA, 2006: *Associated project details for RFA: The impact of climate change & variability on human health (2005).* U.S. Environmental Protection Agency.

U.S. Senate Committee on Homeland Security and Governmental Affairs (CHSGA), 2006: *Hurricane Katrina: A Nation Still Unprepared.* 109th Congress, 2nd Session, S. Rept. 109-322, Washington DC, USA.

Vereen, E., R.R. Lowrance, D.J. Cole, and E.K. Lipp, 2007: Distribution and ecology of campylobacters in coastal plain streams (Georgia, United States of America). *Applied and Environmental Microbiology*, **73(5)**, 1395-1403.

Verger, P., M. Rotily, C. Hunault, J. Brenot, E. Baruffol, and D. Bard, 2003: Assessment of exposure to a flood disaster in a mental-health study. *Journal of Exposure Analysis and Environmental Epidemiology,* **13,** 436-442.

Viboud, C., K. Pakdaman, P-Y. Boelle, M.L. Wilson, M.F. Myers, A.J. Valleron, and A. Flahault, 2004: Association of influenza epidemics with global climate variability. *European Journal of Epidemiology,* **19(11),** 1055-1059.

Visscher, T.L. and J.C. Seidell, 2001: The public health impact of obesity. *Annual Review of Public Health,* **22,** 355-375.

Vose, R., T. Karl, D. Easterling, C. Williams, and M. Menne, 2004: Climate (communication arising): Impact of land-use change on climate. *Nature,* **427(6971),** 213-214.

Vugia, D., A. Cronquist, J. Hadler, *et al.*, 2006: Preliminary FoodNet data on the incidence of infection with pathogens transmitted commonly through food – 10 states, United States, 2005. *MMWR – Morbidity & Mortality Weekly Reports,* **55(14),** 392-395.

Wade, T.J., S.K. Sandu, D. Levy, S. Lee, M.W. LeChevallier, L. Katz, and J.M. Colford, Jr., 2004: Did a severe flood in the Midwest cause an increase in the incidence of gastrointestinal symptoms? *American Journal of Epidemiology*, **159(4),** 398-405.

Wan, S.Q., T. Yuan, S. Bowdish, L. Wallace, S.D. Russell and Y.Q. Luo, 2002: Response of an allergenic species Ambrosia psilostachya (Asteraceae), to experimental warming and clipping: implications for public health. *American Journal of Botany*, **89**, 1843-1846.

Watkins, S.J., D. Byrne, and M. McDevitt, 2001: Winter excess morbidity: is it a summer phenomenon? *Journal of Public Health Medicine,* **23(3),** 237-241.

Wayne, P., S. Foster, J. Connolly, F. Bazzaz and P. Epstein, 2002: Production of allergenic pollen by ragweed (Ambrosia artemisiifolia L.) is increased in CO_2-enriched atmospheres. *Annuals of Allergy Asthma and Immunology*, **88**, 279-82.

Wegbreit, J. and W.K. Reisen, 2000: Relationships among weather, mosquito abundance, and encephalitis virus activity in California: Kern County 1990-98. *Journal of the American Mosquito Control Association,* **16(1),** 22-27.

Weisler, R.H., J.G.I. Barbee, and M.H. Townsend, 2006: Mental health and recovery in the Gulf coast after hurricanes Katrina and Rita. *The Journal of the American Medical Association,* **296(5),** 585-588.

Weisskopf, M.G., H.A. Anderson, S. Foldy, L.P. Hanrahan, K. Blair, T.J. Torok, *et al.*, 2002: Heat wave morbidity and mortality, Milwaukee, Wis, 1999 vs 1995: An improved response? *American Journal of Public Health,* **92(5),** 830-833.

Wellings, F.M., P.T. Amuso, S.L. Chang, and A.L. Lewis, 1977: Isolation and identification of pathogenic *Naegleria* from Florida lakes. *Applied and Environmental Microbiology,* **34(6),** 661-667.

Westerling, A.L., H.G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science,* **313,** 940-943.

Westerling, A.L., A. Gershunov, T.J. Brown, D.R. Cayan, and M.D. Dettinger, 2003: Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society,* 595-604.

Wetz, J.J., E.K. Lipp, D.W. Griffin, J. Lukasik, D. Wait, M.D. Sobsey, T.M. Scott, and J.B. Rose, 2004: Presence, infectivity and stability of enteric viruses in seawater: relationship to marine water quality in the Florida Keys. *Marine Pollution Bulletin,* **48**, 700-706.

Whitman, S., G. Good, E.R. Donoghue, N. Benbow, W. Shou, and S. Mou, 1997: Mortality in Chicago attributed to the July 1995 heat wave. *American Journal of Public Health,* **87(9),** 1515-1518.

Wilkinson, P, S. Pattenden, B. Armstrong, A. Fletcher, R.S. Kovats, P. Mangtani, *et al.*, 2004: Vulnerability to winter mortality in elderly people in Britain: population based study. *British Medical Journal,* **329(7467),** 647.

Woodruff, R.E., S. Hales, C.D. Butler, and A.J. McMichael, 2005: Climate change health impacts in Australia: Effects of dramatic CO2 emissions reductions. Available at: http://wwwamacomau/webnsf/doc/WEEN-6HA6MS/$file/Climate_Change_Impacts_Health_Reportpdf.

World Health Organization, 1999: Leptospirosis worldwide, 1999. *Weekly Epidemiological Record*, **74**, 237-244.

Xu, H.Q. and B.Q. Chen, 2004: Remote sensing of the urban heat island and its changes in Xiamen City of SE China. *Journal of Environmental Sciences,* **16(2),** 276-281.

Zender, C.S. and J. Talamantes, 2006: Climate controls on valley fever incidence in Kern County, California. *International Journal of Biometeorology* **50**, 174-82.

Ziska, L.H., S.D. Emche, E.L. Johnson, K. George, D.R. Reed and R.C. Sicher, 2005: Alterations in the production and concentration of selected alkaloids as a function of rising atmospheric carbon dioxide and air temperature: implications for ethno-pharmacology. *Global Change Biology*, **11**, 1798-1807.

Zhuang, R-Y., L.R. Beuchat, and F.J. Angulo, 1995: Fate of *Salmonella* Montevideo on and in raw tomatoes as affected by temperature and treatment with chlorine. *Applied and Environmental Microbiology,* **61(6),** 2127-2131.

2.9 Boxes

BOX 2.1 Vulnerable Populations and Hurricane Katrina

In 2005, Hurricane Katrina caused more than 1,500 deaths along the Gulf Coast, and many of these victims were members of vulnerable subpopulations, such as hospital and nursing-home patients, older adults who required care within their homes, and individuals with disabilities (U.S. CHSGA, 2006). 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). Six of the fifteen deaths indirectly related to the hurricane and its immediate aftermath 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).

BOX 2.2 Heatwave Early Warning Systems

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

Box 2.3: Quick Tips for Responding to Excessive Heat waves

For the Public

Do

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

Don't

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

Useful Community Interventions

For Public Officials

Send a clear public message

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

Inform the public of anticipated EHE conditions

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

Assist those at greatest risk

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

Provide access to additional sources of information

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

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

Source: U.S. EPA, 2006

2.10 Tables

Table 4.1 Projections of Impacts of Climate Change on Heat-Related Mortality

Location	Period	Adaptation considered	Projected Impact on Heat-Related Deaths
Lisbon, Portugal[1]	2020s, 2050s compared to 1980-1998	yes	Increase of 57%-113% in 2020s, 97-255% in 2050s, depending on adaption
5 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 1970-98	yes	Decrease after 2010 due to adaptation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

during a heatwave extreme event

2.11 Figures

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

(Curriero *et al.* 2002)

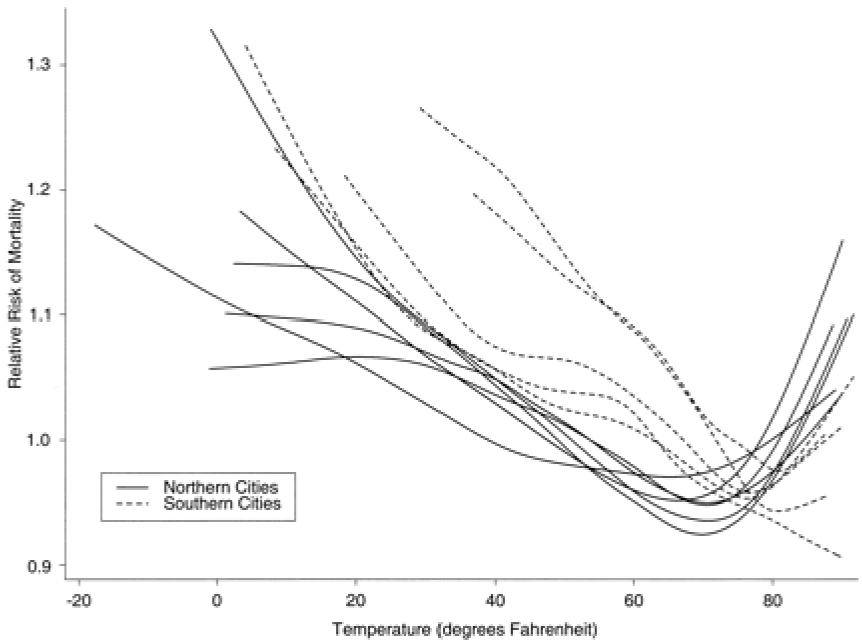
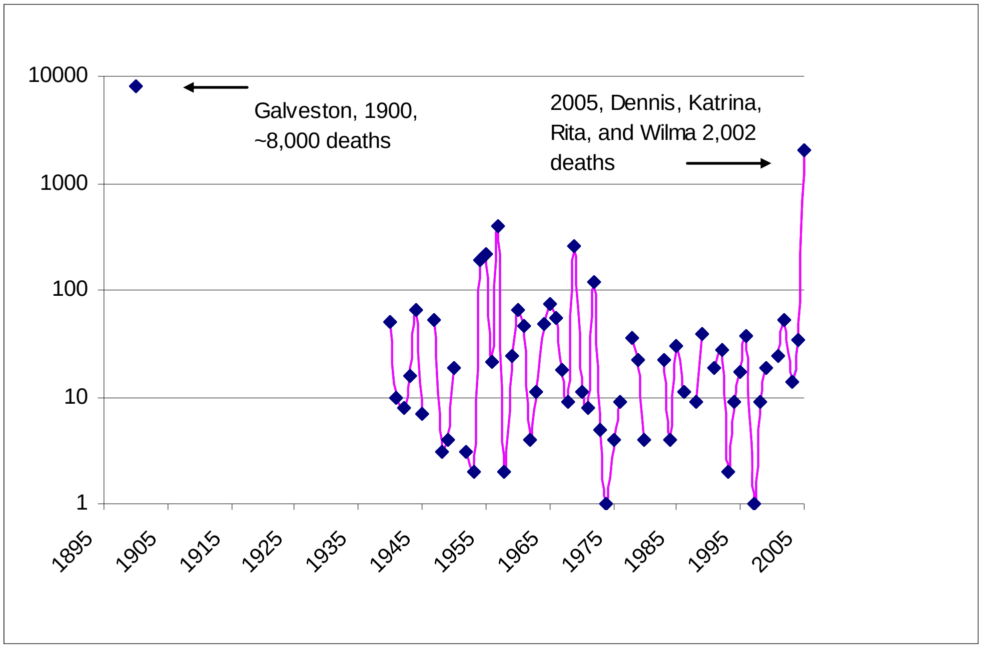
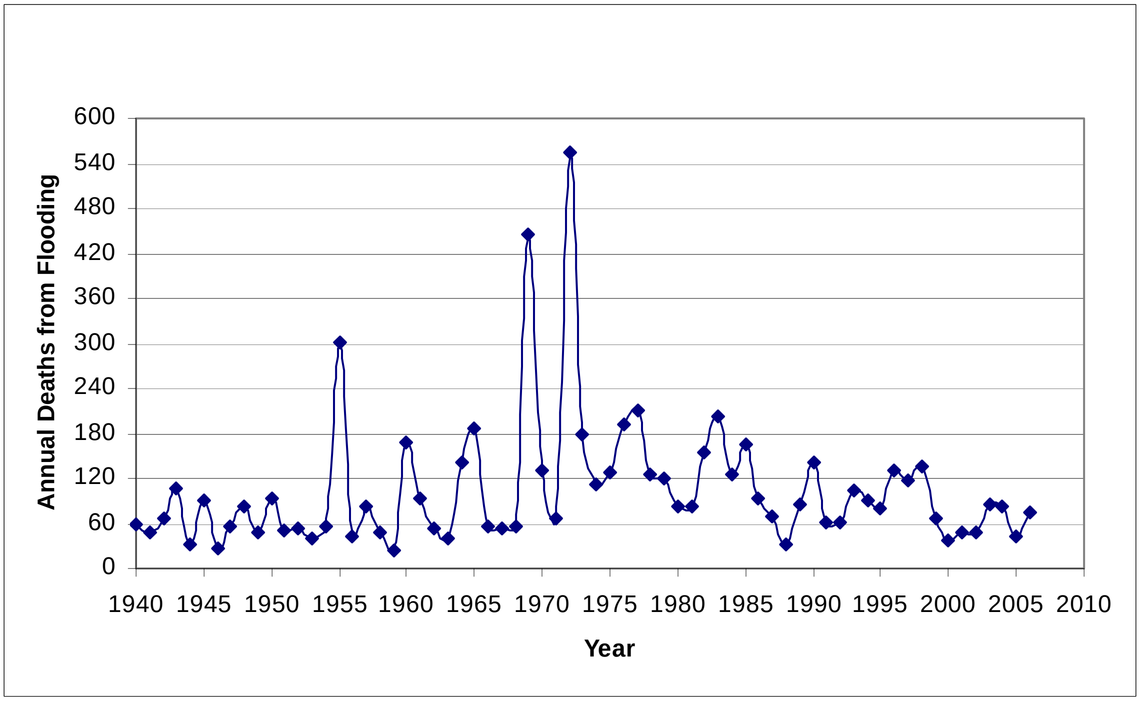


Figure 2.2. Annual Deaths Attributed to Hurricanes in the United States, 1900 and 1940-2005



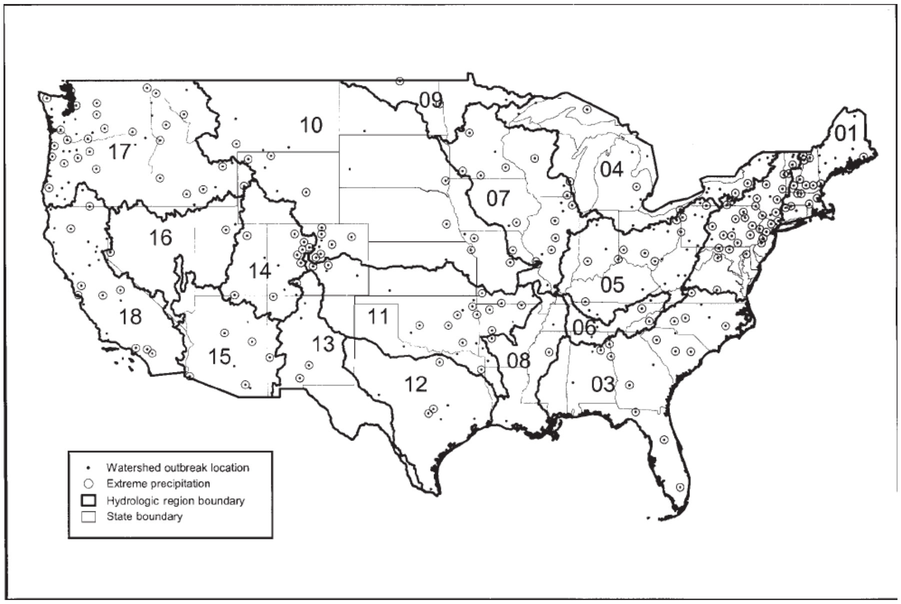
Source: NOAA, 2007

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



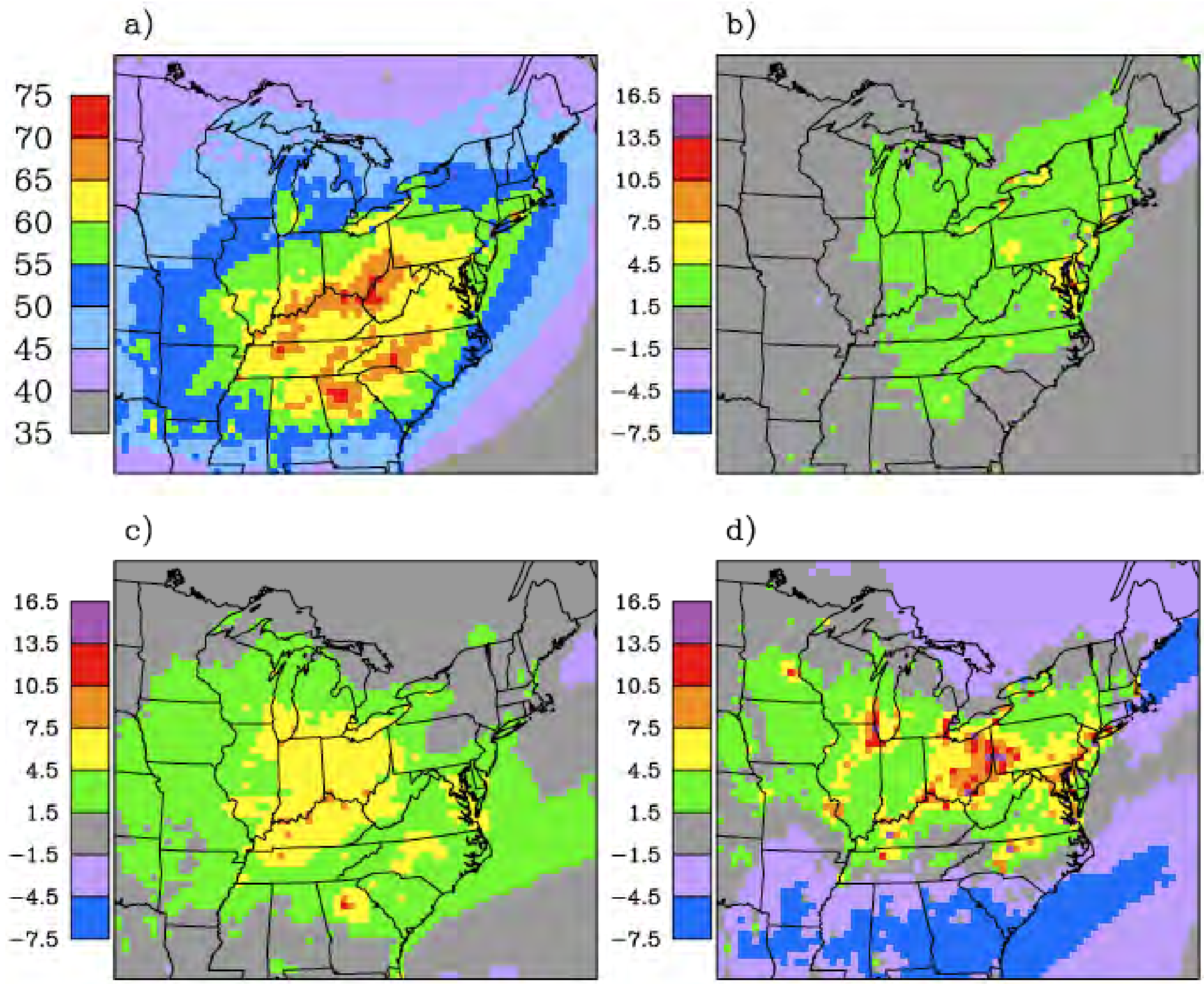
Source: NOAA, 2007a

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



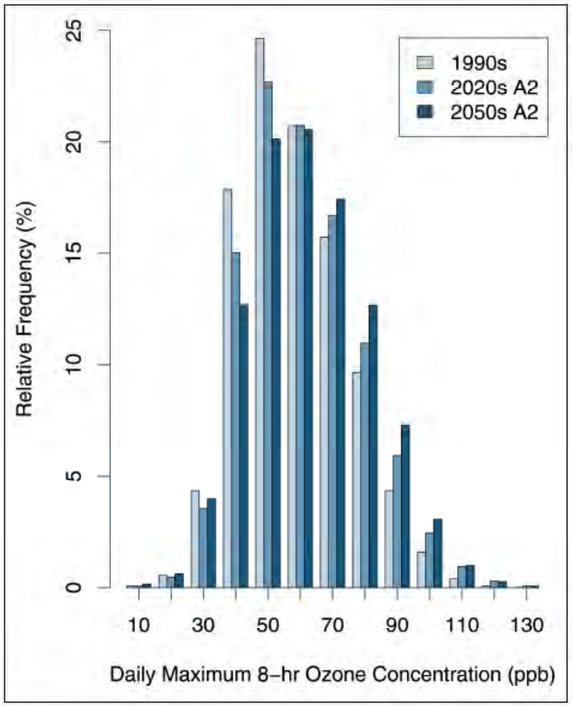
Source: Curriero *et al.*, 2001

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



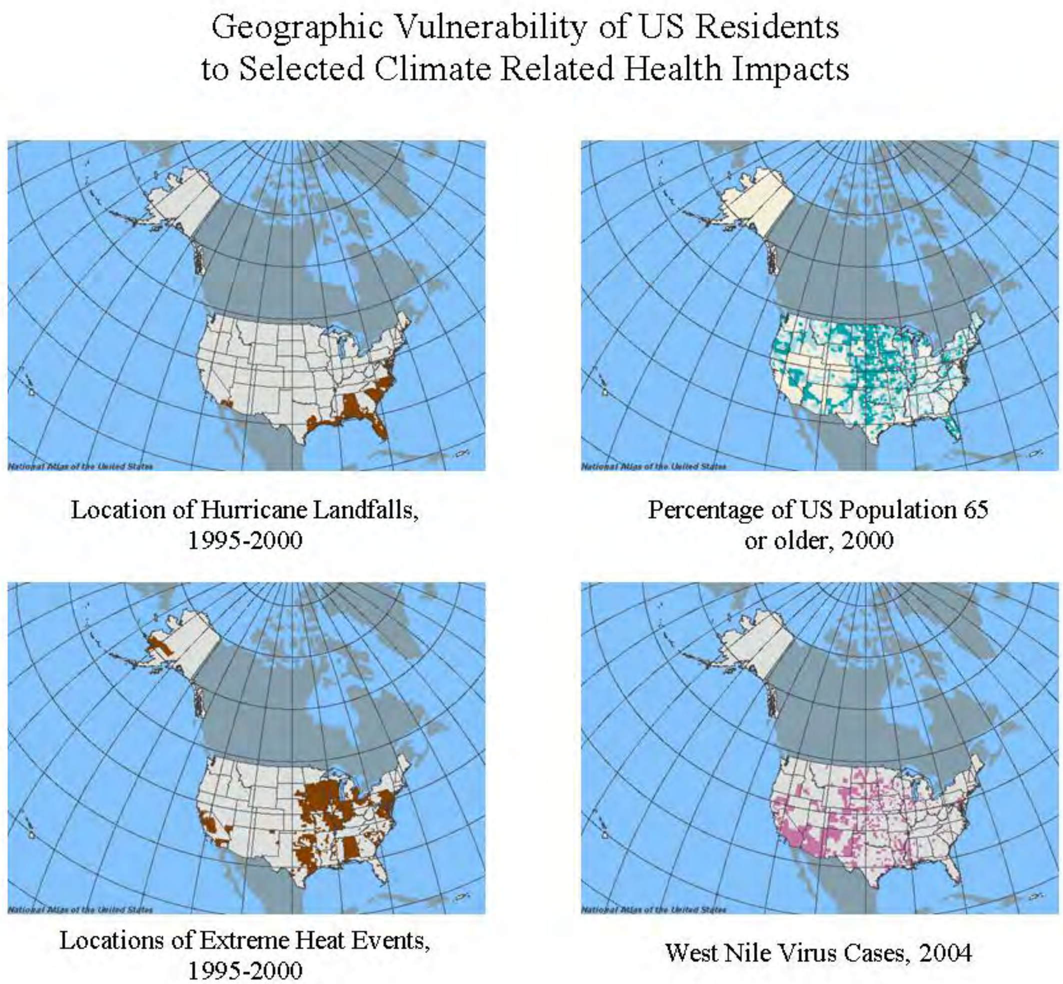
Source: Hogrefe *et al.*, 2004a.

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



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

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



Synthesis and Assessment Product 4.6

Chapter 3

Effects of Global Change on Human Settlements

Lead Author: Thomas J. Wilbanks, Oak Ridge National Laboratory

Contributing Authors: Paul Kirshen, Tufts University; Dale Quattrochi, NASA/Marshall Space Flight Center; Patricia Romero-Lankao, NCAR; Cynthia Rosenzweig, NASA/Goddard; Matthias Ruth, University of Maryland; William Solecki, Hunter College; Joel Tarr, Carnegie Mellon University

Contributors: Peter Larsen, University of Alaska-Anchorage; Brian Stone, Georgia Tech

Table of Contents

3.1 Introduction

3.1.1 Purpose

Human settlements are where people live and work, including all population centers ranging from small rural communities to densely developed metropolitan areas. This chapter addresses climate change impacts, both positive and negative, on human settlements in the United States. First, the chapter summarizes current knowledge about the vulnerability of human settlements to climate change, in a context of concurrent changes in other non-climate factors. Next, the chapter summarizes opportunities within settlements for adaptation to climate change. Finally, the chapter provides an overview of recommendations for expanding the current knowledge base with respect to climate change and human settlements..

3.1.2 Background

Events such as Hurricane Katrina in 2005 and electric power outages during the hot summer of 2006 have demonstrated how climate-related events can dramatically impact U.S. settlements. Climate affects the costs of assuring comfort at home and work. Climate affects inputs for a good life: water, products and services from agriculture and forestry, pleasures and tourist potentials from nature, biodiversity, and outdoor recreation. Climate also affects the presence and spread of diseases and other health problems, and it is associated with threats from natural disasters, including floods, fires, droughts, wind, hail, ice, and heat and cold waves.

Some U.S. settlements may find opportunities in climate change. Warmer winters are not necessarily undesirable. Periods of change tend to reward forward-looking, effectively-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. 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 technological and social innovations take place.

Meanwhile, the pattern of human settlements in the U.S. is changing. In addition to 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).

Modern information technologies are enabling people to perform what were historically urban functions from relatively remote locations (Riebsame, 1997).

3.1.3 Current State of Knowledge

The current knowledge base provides limited grounds for developing conclusions and recommendations related to climate impacts on human settlements. In many cases, the best that can be done is to sketch out the issue "landscape" that should be considered by both policy-makers and the research community as a basis for further discussion, offering illustrations from the relatively small research literature that is now available.

The fact is that little research has been done to date specifically on the effects of climate change in U.S. cities and towns. Reasons appear to include (i) limitations in capacities to project climate change impacts at the geographic scale of a metropolitan area (or smaller) and (ii) the fact that none of the federal agencies currently active in climate science research has a clear responsibility for settlement impact issues. Improvements in our understanding of the impacts of and adaptation to climate change across different sectors and geographic regions, differential vulnerabilities, and in designing interventions to build resilience are all needed (NRC, 2007).

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 historical analogs of responses of urban areas to significant environmental changes. A text box entitled *Historical Perspective of the U.S. Urban Responses to Environmental Change* is included as Box 3.1. This perspective examines how American cities have been affected by environmental change over the past two centuries. But this is little more than a place to start.

At the current state of knowledge, <u>vulnerabilities</u> to possible impacts are easier to project than actual <u>impacts</u> because they *estimate risks or opportunities* associated with possible consequences rather than *estimating the consequences* themselves, which requires far more detailed information about future conditions. Vulnerabilities are shaped not only by existing exposures, sensitivities, and adaptive capacities but also by the ability of settlements to develop responses to risks.

3.2 Climate Change Impacts and the Vulnerabilities of Human Settlements

This section examines possible impacts of climate change on settlements in the U.S. including the determinants of vulnerability to such impacts and how those impacts could affect settlement patterns and various systems related to those patterns.

3.2.1 Determinants of vulnerability

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 decision-making (as for other relatively local-scale impact questions) but moreover 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.

Vulnerabilities to or opportunities from climate change are related to three factors, both in absolute terms and in comparison to other elements (Clark et al., 2000):

(1) *Exposure to climate change*. To what climate changes are settlements likely to be exposed: Changes in temperature or precipitation? Changes in storm exposures and/or intensities? Changes in sea level?

(2) *Sensitivity to climate change.* If primary climate changes 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 variation.

(3) *Adaptive 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 while realizing new opportunities?

3.2.2 Impacts of Climate Change on Human Settlements

Impacts of climate change on human settlements vary regionally (see Table 3.2 and Vignettes below), and generally relate to some of the following issues:

1 *Effects on health*. It is well-established that higher temperatures in urban areas are related to higher levels of ozone which cause respiratory and cardiovascular 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 mortality 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 Chapter 2).

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 (Gleick et al., 2000; Kirshen, 2002; Ruth *et al.*, 2007). Moreover, storms, floods, and other severe weather events may affect other infrastructure, including sanitation systems, 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.*, 2007). An example is an interruption in energy supply, which increases heat stress for vulnerable populations (Ruth *et al.*, 2006a). Many of the infrastructures in older cities are aging and are already under stress from increasing demands.

3 *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 Vignettes in Boxes 3.2 and 3.3). 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.*, 2007).

4 *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 3.4: Climate Change Impacts on the 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. The maps in this box demonstrate how the built environment creates and retains heat in metropolitan settings.

5 *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).

6 *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 unstable is likely to suffer, especially in areas with relatively limited resources (Sherbinin *et al.*, 2006).

7 *Effects on vulnerable populations* (see Chapter 1*).* Where climate change stresses 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 on vulnerable regions.* 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). 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; IPCC, 2007).

Different combinations of circumstances are likely to cause particular concerns for cities and towns in the United States as they consider possible implications of climate change.

3.2.3. The Interaction of Climate Impacts with Non-Climate Factors.

In general, 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 rather than climate change per se (IPCC, 2007). 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.

In many cases, these interactions involve not only direct impacts such as warming or more or less precipitation but, sometimes more important, second, third, or higher-order impacts, as direct impacts cascade through urban systems and other settlement-determined processes (e.g., warming which affects urban air pollution which affects health which affects public service requirements which affect social harmony: Kirshen *et al*., 2007). 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 this “multi-stress” perspective, it is highly likely that effects of climate change on settlements are shaped by certain “thresholds,” below which effects are incidental but beyond where effects quickly become major when a limiting or inflection point is reached. An example might be a city’s capacity to cope with sustained heat stress combined with a natural disaster. In general, these climate-related thresholds for human settlements in the U.S. are not well-understood. For multi-stress assessments of thresholds, changes in climate extremes are very often of more concern than changes in climate averages. 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 have not always been projected by climate change models (see Figure 3.2).

Finally, human settlements may be affected by climate change mitigation initiatives as well as by climate change itself. Examples include effects on policies related to energy sources and uses, environmental emissions, and land use. 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 term effects are less predictable.

As climate change affects settlements in the U.S., impacts are realized at the intersection of climate change with underlying forces. Most of the possible effects are linked with changes in regional comparative advantage, with consequent migration of population and economic activities (Ruth and Coelho, in press). Examples of these complex interactions and issues include:

1 *Regional risks and availability of insurance*. It is possible that regions exposed to risks from climate change will see movement of population 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, 2007), 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).(citation)

3 *Shifts in comparative living costs, risks, and amenities.* 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. (citation: SAP 4.5)

5 *Urban "footprints" on other areas*. Resource requirements for urban areas involve larger areas than their own bounded territories alone. 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 settlements, along with their resource capacities for their inputs and destinations of their outputs, climate change could affect the nature, size, and geographic distribution of these footprints.

Human settlements are foci for many economic, social, and governmental processes, and historical experience has shown 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, 2007).

3.2.4 Realizing Opportunities from Climate Change in the U.S.

Climate change can have positive as well as negative implications for settlements. Examples of potential 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 climate change can be that its capacity to stimulate a broader discussion of what sustainability means for settlements (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, others may be "winners," as changes in temperature or precipitation result in added economic opportunities (see the following section), at least if climate change is not severe. 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.

3.2.5 Examples of Impacts on Metropolitan Areas 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 (see Table 3.2 and Boxes 3.2 and 3.3). 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: This assessment concluded that impacts of climate change on this metropolitan area are likely to be primarily negative over the long term, with potentially significant costs increasing as the magnitude of climate change increases, although there are substantial uncertainties. (Rosenzweig and Solecki, 2001a; also see Rosenzweig and Solecki, 2001b, and Solecki and Rosenzweig, 2006).

(2) Boston: This assessment 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 (Kirshen *et al.*, 2004; also see Kirshen *et al.*, 2006 and 2007)

Other U.S. studies include Seattle (Hoo and Sumitani, 2005) and Los Angeles (Koteen *et al.*, 2001) (Table 3.1). 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 reported by Klinenberg (2003).

3.3 Opportunities for Adaptation of Human Settlements to Climate Change

Settlements are important in considering prospects for adaptation to climate change, both because they represent concentrations of people and because buildings and other infrastructures offer ways to manage risk and monitor/control threats associated with climate extremes and other non-climate stressors.

Where climate change presents risks of adverse impacts for U.S. settlements and their populations, there are two basic options 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 3.5: Roles of Settlements in Climate Change Mitigation). The second response is to consider strategies for **adaptation**, 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; 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 strategies will be important to the well-being of U.S. settlements as climate change evolves 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, unchanged by adaptation. 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. Whether or not adaptation to climate change occurs in U.S. cities is therefore a potentially 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).

3.3.1. Perspectives on Adaptation by Settlements

For decision-makers in U.S. settlements climate change is yet one more source of possible risks that need to be addressed. Climate change is different as an issue because it is relatively long-term in its implications, future impacts are uncertain, 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. 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.

Cities and towns have used both "hard" approaches such as developing infrastructure and "soft" approaches such as regulations to address impacts of climate variability. 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 socioeconomic changes; thus, if climate change is properly institutionalized into the urban planning process, it can be handled as yet another uncertainty.

3.3.2 Major Categories of Adaptation Strategies

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

1 *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 and 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, and assistance for the less-advantaged (including actions by the private insurance sector as a likely driving force).

2 *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).

3 *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), waste reduction and advanced waste treatment, and better warning systems and controls. Physical design changes for long-lived infrastructure may also be appropriate, such as building water-treatment or storm-water runoff outflow structures based on projected sea level rather than the historical level.

4 *Institutional change to improve adaptive 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, adopting sustainable community development practices, and monitoring changes in physical infrastructures at an early stage (Wilbanks *et al.*, 2007). Policy instruments include zoning, building and design codes, terms for financing, and early warning systems (Kirshen, Ruth, and Anderson, 2005).

5 *"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."

3.3.3 Examples of Current Adaptation Strategies

In most cases in the U.S., settlements have been more active in climate change mitigation than climate change adaptation (see Box 3.5), but there are some indications that adaptation is growing as a subject of interest (Solecki and Rosenzweig, 2005; Ruth, 2006). Bottom-up grassroots activities currently under way in the U.S. are considerable, and that number appears to be growing. 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, 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 governments 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 ameliorate 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 "green" 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). The "Excessive Heat Events Guidebook" developed by the Environmental Protection Agency in collaboration with NOAA, CDC, and DHS provides information for municipal officials in the event of an excessive heat event: http://www.epa.gov/hiri/about/heatguidebook.html.

3.3.4: Strategies to Enhance Adaptive Capacity

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.

3.4. Conclusions

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 takes place in the context of a variety of factors driving an area's development: it is likely to be a secondary factor in most places, 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 basins susceptible to flooding, arid areas where water scarcity is a pressing issue, and areas whose economic bases are climate-sensitive (very likely).

3 The main impact concerns, in areas other than Alaska, 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 current climate change projections, the potential 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 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).

3.5 Expanding the Knowledge Base

A number of sources, including NACC, 1998; Parson *et al.*, 2003; Ruth, 2006; and Ruth, Donaghy, and Kirshen, 2004, have considered research pathways for improving the understanding of effects of climate change on human settlements in the United States. The following list suggests a number of research topics that would help expand the knowledge base about the linkages between climate change and human settlements.

- Advance understanding of settlement vulnerabilities, impacts, and adaptive responses in a variety of different local contexts around the country through case studies. In addition to identifying vulnerable settlements, these studies should also identify vulnerable populations (such as the urban poor and native populations on rural and/or tribal lands) that have limited capacities for response to climate change, within those settlements. Better understanding of climate change at the community scale would provide a basis for adaptation research that addresses social justice and environmental equity concerns.

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

- Improve 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.

- Design practically implementable, socially acceptable strategies for shifting human populations and activities away from vulnerable locations.

- Improve the understanding of vulnerabilities of urban inflows and outflows to climate change impacts, as well as second and third-order impacts of climate change in urban environments, including interaction effects among different aspects of the urban system.

- Improve the understanding of the relationships between settlement patterns (both regional and intra-urban) and resilience/adaptive capacity.

- Improve understanding of how urban decision-making is changing as populations become more heterogeneous and decisions become more decentralized, especially as this affects adaptive responses.

- Review 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.

- Evaluate and document experiences with urban/settlement climate change responses while involving decision-making, research and stakeholder communities more actively in discussions of climate change impacts and response issues. Focus attention on the costs, benefits, and possible limits and potentials of adaptation to climate change vulnerabilities in U.S. cities and smaller settlements.

- Improve tools and approaches for infrastructure planning and design to reduce exposure and sensitivity to climate change effects while increasing adaptive capacity.

- Enhance coordination within federal government agencies to improve understanding about impacts, vulnerabilities and responses to climate change for the nation's cities and smaller settlements. Connections with U.S. urban decision-makers can enable integration of climate change considerations into what they do with building codes, zoning, lending practices, etc. as mainstreamed urban decision processes.

3.6 References

Amato, A., M. Ruth, P. Kirshen, and J. Horwitz, 2005: Regional energy demand responses to climate change: Methodology and application to the Commonwealth of Massachusetts. *Climatic Change,* **71(1),** 175-201.

ACIA, 2004: *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Arctic Climate Impact Assessment, Cambridge University Press, Cambridge.

AIACC: Assessments of Impacts and Adaptations to Climate Change in Multiple Regions and Sectors. Available at: http://www.aiaccproject.org [Accessed 25 January 2007].

Association of American Geographers (AAG), 2003: *Global Change In Local Places: Estimating, Understanding, And Reducing Greenhouse Gases* [GCLP Research Team: Kates, R., T. Wilbanks, and R. Abler (eds.)]. Association of American Geographers, Cambridge University Press, Cambridge, MA.

Betsill, M.M., 2001: Mitigating climate change in US cities: Opportunities and obstacles. *Local Environment,* **4,** 393-406.

Bloomfield, J., M. Smith, and N. Thompson, 1999: *Hot Nights in the City: Global Warming, Sea-Level Rise and the New York Metropolitan Region.* Environmental Defense Fund, Washington, DC, USA.

Bonsignure, R., 2003: *Urban Green Space: Effects on Water and Climate,* Center for American Urban Landscape, Design Brief Number 3, University of Minnesota.

Brazel, A.J. and D.A. Quattrochi, 2005: Urban climates. In: *Encyclopedia of World Climatology*. [J.E. Oliver, (ed.)]. Springer, Dordrecht, The Netherlands, pp. 766-779.

Bulkeley, H. and M. Betsill, 2003: *Cities and Climate Change; Urban Sustainability and Global Environmental Governance.* Routledge, London.

City of New York, 2005: *New York City's Water Supply System.* The City of New York Department of Environmental Protection, New York.

Clark, W.C., et al., 2000: *Assessing Vulnerability to Global Environmental Risks*. Discussion Paper 200-12, Environment and Natural Resources Program, Kennedy School of Government, Harvard University, Cambridge, MA.

Colten, C.E., 2005. *An Unnatural Metropolis: Wrestling New Orleans from Nature.* Baton Rouge: Louisiana State University.

Congressional Black Caucus Foundation, 2004: *African Americans and Climate Change: An Unequal Burden*. Redefining Progress, Washington, DC, USA.

Decker, E., S. Elliot, F. Smith, D. Blake, and F. Rowland, 2000: Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment,* **25,** 685-740.

Easterling, W. E., B. H. Hurd, and J. B. Smith, 2004: *Coping with Global Climate Change: The Role of Adaptation in the United States*, prepared for the Pew Center on Global Climate Change**.**

Emanuel, K.A., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436,** 686-688.

Estes, Jr., M.D., D. Quattrochi, and E. Stasiak, 2003: The urban heat island phenomena: How its effect can influence environmental decision making in your community. *Public Management*, **85,** 8-12.

Folke, C., A. Janssen, J. Larsson, and R. Costanza, 1997: Ecosystem appropriation by cities, *Ambio*, **26,** 167-172.

Franco, G., 2005: *Climate Change Impacts and Adaptation in California*, prepared for the California Energy Commission.

Gleick, P.H. et al, 2000: *Water: The Potential Consequences of Climate Variability and Change.* A Report of the National Water Assessment Group, U.S. Global Change Research Program, U.S. Geological Survey, U.S. Department of the Interior, and the Pacific Institute. Oakland, CA.

Haites, E., K. Caldeira, P. Romero Lankao, A. Rose, and T. Wilbanks, 2007: What are the options that could significantly affect the carbon cycle? In: *State of the Carbon Cycle Report (SOCCR).* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration. National Climatic Data Center.

Hartwig, R., 2006: *Hurricane Season Of 2005, Impacts On U.S. P/C Markets, 2006 And Beyond.* Presentation to the Insurance Information Institute, New York, NY. Available at: http://www.iii.org/media/presentations/katrina/ [Accessed on 17 April 2006].

Hoo, W. and M. Sumitani, 2005: *Climate Change Will Impact the Seattle Department of Transportation.* Office of the City Auditor, Seattle, Washington, USA.

Hunter, J. R., 2006: Testimony before the Committee on Banking, Housing and Urban Affairs of the United States Senate Regarding Proposals to Reform the National Flood Insurance Program.

ICLEI, 2006: Available at: http://www.iclei.org.

IPCC, 2001a: Human settlements, energy, and industry. In: IPCC, 2001b.

IPCC, 2001b: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, Cambridge, 967 pp.

IPCC, 2001c: Insurance and other financial services. In: IPCC, 2001b.

IPCC, forthcoming: *Industry, Settlement, and Society*. Intergovernmental Panel on Climate Change (IPCC), Working Group II, Fourth Assessment Report, Chapter 7. (not for citation before WG II Plenary, April 2-6, 2007, but can be cited after that)

Kinney, P., J. Rosenthal, C. Rosenzweig *et al.,* 2006: Assessing potential public health impacts of changing climate and land uses: The New York climate and health project. In: *Regional Climate Change and Variability* [Ruth, M., K. Donaghy, and P. Kirshen, (eds.)], New Horizons in Regional Science, Edward Elgar, Cheltenham, UK 2006.

Kirshen, P. H., 2002: Potential impacts of global warming in eastern Massachusetts. *Journal of Water Resources Planning and Management*, **128(3),** 216-226.

Kirshen, P.H., M. Ruth, W. Anderson, T. R. Lakshmanan, S. Chapra, W. Chudyk, L. Edgers, D. Gute, M. Sanayei, and R. Vogel, 2004: *Climate's Long-term Impacts on Metro Boston*. Final Report to the U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC, USA.

Kirshen, P., M. Ruth and W. Anderson. 2005: Climate change in metropolitan Boston, *New England Journal of Public Policy*, **20**(2), 89-103.

Kirshen, P., M. Ruth, and W. Anderson, 2006: Climate's long-term impacts on urban infrastructures and services: The case of metro Boston. In: *Climate Change and Variability: Impacts and Responses* [M. Ruth, P. Kirshen, and Donaghy, (eds.)]. Edward Elgar, Cheltenham, UK, pp. 190-252.

Kirshen, P., M. Ruth, and W. Anderson, 2007: Interdependencies of urban climate change impacts and adaptation strategies: A case study of metropolitan Boston. *Climatic Change*, 66: 105-122.

Klinenberg, E., 2003: *Heat Wave: A Social Autopsy of Disaster in Chicago*. University of Chicago, Chicago, IL, USA.

Koteen, L., J. Bloomfield, T. Eichler, C. Tonne, R. Young, H. Poulshock, and A. Sosler, 2001: *Hot Prospects: The Potential Impacts of Global Warming on Los Angeles and the Southland*. Environmental Defense, Washington, DC, USA.

Kretch, S. III, 1999. *Myth and History: The Ecological Indian.* New York: W.W. Norton.

Larsen, Peter, O.S. Goldsmith, O. Smith, and M. Wilson, 2007: *A Probabilistic Model to Estimate the Value of Alaska Public Infrastructure at Risk to Climate Change*. ISER Working Paper, Institute of Social and Economic Research, University of Alaska, Anchorage, AK, USA.

Lo, C.P. and D.A. Quattrochi, 2003: Land-use and land-cover change, urban heat island phenomenon, and health implications: A remote sensing approach. *Photogrammetric Engineering and Remote Sensing*.

London Climate Change Partnership, 2004: *London's Warming, A Climate Change Impacts in London Evaluation Study*. London, 293 pp.

McCarthy, K., D. Peterson, N. Sastry, and M. Pollard, 2006: *The Repopulation of New Orleans after Hurricane Katrina*. Rand, Santa Monica, CA, USA.

Molina, M. et al., 2005: *Air Quality in the Mexico Megacity: An Integrated Assessment.* Kluwer, Dordrecht, Netherlands.

Morehouse, B. G., Christopherson, M. Crimmins, B. Orr, J. Overpeck, T. Swetnam, and S. Yool, 2006: "Modeling interactions among wild land fire, climate and society in the context of climatic variability and change in the southwest U.S.," Ruth, Donaghy, and Kirshen, op. cit.

NACC 1998: *Climate Change and a Global City: An Assessment of the Metropolitan East Coast Region*, Columbia Earth Institute/NASA Goddard Institute for Space Studies.

NACC, 2000: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. U.S. Global Change Research Program, Washington, DC, USA.

NACC, 2001: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, U.S. Global Change Research Program, Washington, DC, USA.

Neumann, J.E., G. Yohe, R. Nichols, and M. Manion, 2000: *Sea Level Rise and Global Climate Change: A Review of Impacts to U.S. Coasts*. Pew Center on Global Climate Change, Washington, DC, USA.

NOAA, 2005: *Population Trends Along the Coastal United States, 1980-2008*. Available at: http://www.oceanservice.noaa.gov/programs/mb/supp_cstl_population.html.

Parris, T., 2007: Green buildings. *Environment*, **49(1),** 3.

Parson, E., *et al.*, 2003: Understanding climatic impacts, vulnerabilities, and adaptation in the United States: Building a capacity for assessment, *Climatic Change,* (**57)**, 9–42.

Patz, J.A. and J.M. Balbus, 2001: Global climate change and air pollution. In: *Ecosystem Change And Public Health. A Global Perspective* [Aron J.L. and J.A. Patz (eds.)]. The Johns Hopkins University Press, Baltimore, pp 379–408.

Quattrochi, D.A., J.C. Luvall, D.L. Rickman, M.G. Estes, Jr., C.A. Laymon, and B.F. Howell, 2000: A decision support system for urban landscape management using thermal infrared data. *Photogrammetric Engineering and Remote Sensing*, **66,** 1195-1207.

Rabe, B., 2006: *Second Generation Climate Policies in the States*. Paper presented at the Conference Climate Change Politics in North America, Washington DC, 18-19 May 2006. Available at: http://www.wilsoncenter.org/ecsp.

Ridd, M.K., 2006: 10.3 Environmental dynamics of human settlements. In: *Remote Sensing of Human Settlements, Manual of Remote Sensing, Third Edition, Volume 5* [Ridd, M.K. and J.D. Ripple, (eds.)]. American Society for Photogrammetry and Remote Sensing, Bethesda, MD, USA, pp. 564-642.

Riebsame, W., 1997: *Atlas of the New West: Portrait of a Changing Region.* New York: W.W. Morton.

Romero Lankao, P., 2007: Are we missing the point? Particularities of urbanization, sustainability and carbon emissions in Latin American cities. *Urbanization and Environment*, **19(1)**.

Rosenzweig, C., W. Solecki, C. Paine, V. Gornitz, E. Hartig, K. Jacob, D. Major, P. Kinney, D. Hill, and R. Zimmerman, 2000: *Climate Change and a Global City: An Assessment of the Metropolitan East Coast Region*. U.S. Global Change Research Program. Available at: http://metroeast_climate.ciesin.columbia.edu [Accessed 19 January 2007].

Rosenzweig, C., and W. Solecki, eds. 2001a: *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change – Metro East Coast*. Columbia Earth Institute, New York.

Rosenzweig, C. and W.D. Solecki, 2001b: Global environmental change and a global city: Lessons for New York. *Environment*, **43(3),** 8-18.

Rosenzweig, C., S. Gaffin, and I. Parshall (eds.), 2006a: *Green Roofs In The New York Metropolitan Region*. Research Report, Columbia University Center for Climate Systems Research and NASA Goddard Institute for Space Studies, New York.

Rosenzweig, C., W. Solecki, and R. Slosberg, 2006b: *Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces*. Final Report, New York City Regional Heat Island Initiative, Prepared for the New York State Energy Research and Development Authority, NYSERDA Contract #6681, New York.

Rosenzweig, C., Solecki, W.D., Parshall, L., Chopping, M., Pope, G., and Goldberg, R, 2005: Characterizing the urban heat island in current and future climates in New Jersey, *Global Environ. Change B Environ. Hazards*, (**6**), 51-62.

Ruth, M. (ed.), 2006: *Smart Growth and Climate Change*. Edward Elgar Publishers, Cheltenham, England, 403 pp.

Ruth, M., A. Amato, and P. Kirshen, 2006a: Impacts of changing temperatures on heat-related mortality in urban areas: The issues and a case study from metropolitan Boston. In: *Smart Growth and Climate Change* [Ruth, M. (ed.)]. Edward Elgar Publishers, Cheltenham, England, pp. 364 – 392.

Ruth, M., K. Donaghy, and P.H. Kirshen (eds.), 2006b: *Regional Climate Change and Variability: Impacts and Responses*. Edward Elgar Publishers, Cheltenham, England, 260 pp.

Ruth, M. and A-C Lin, 2006c: Regional energy and adaptations to climate change: Methodology and application to the state of Maryland, *Energy Policy*, (**34)** 2820-2833.

Ruth, M., C. Bernier, N. Jollands, N. Golubiewski, 2007: Adaptation to urban water supply infrastructure to impacts from climate and socioeconomic changes: The case of Hamilton, New Zealand. *Water Resources Management*, **(21)**, 1031-1045.

Ruth, M. and D. Coelho. In press: Managing the interrelations among urban infrastructure, population, and institutions. *Global Environmental Change.*

Selin, H. and S. D. VanDeveer, 2006: Political science and prediction: What's next for U.S. climate change policy?, *Review of Policy Research* (forthcoming).

Sherbinin, A., A. Schiller, and A. Pulsipher, 2006: The vulnerability of global cities to climate hazards. *Environment and Urbanization,* **12(2),** 93-102.

Solecki, W.D. and C. Rosenzweig, 2006: Climate change and the city: Observations from metropolitan New York. In: *Cities and Environmental Change*, [Bai, X. (ed.)]. Yale University Press, New York.

Solecki, W. and R. Leichenko, 2006: Urbanization and the metropolitan environment. *Environment,* **48(4),** 8-23.

Steinberg, T., 2006. *Acts of God: The Unnatural History of Natural Disaster in America.* New York: Oxford.

Stone, B., 2006: Physical planning and urban heat island formation, 2006. In: *Smart Growth and Climate Change* [Ruth, M. (ed.)]. Edward Elgar Publishers, Cheltenham, England, pp. 318-341.

Vale, L.J. , and T J. Campanella, 2005. *The Resilient City: How Modern Cities Recover from Disaster,* New York: Oxford.

Wilbanks, T.J., 2003: Integrating climate change and sustainable development in a place-based context. In: *Climate Policy*. Supplement on Climate Change and Sustainable Development, November 2003, pp. 147-154.

Wilbanks, et al., 2007: Toward An Integrated Analysis Of Mitigation And Adaptation: Some Preliminary Findings. In: *Challenges in Integrating Mitigation and Adaptation as Responses to Climate Change, special issue, Mitigation and Adaptation Strategies for Global Change* [Wilbanks, Klein, and Sathaye, (eds.)]. Forthcoming 2007.

Young, B., 2002: Thinking clean and green. *Georgia Trend,* **18,** 93-100.

3.7 Boxes

BOX 3.1: U.S. URBAN RESPONSES TO ENVIRONMENTAL CHANGE: A HISTORICAL PERSPECTIVE

Over time, American cities have been affected by environmental change. City founders often showed an important disregard with respect to siting of settlements, focusing on aspects of location such as commercial or recreational opportunities rather than on risks such as flood potential, limited water, food or fuel supplies, or the presence of health threats. Oftentimes settlers 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 commercial buildings. The building of wastewater and water supply systems had the effect of altering regional hydrology and creating large vulnerabilities. In other cases settlers concluded that the weather was changing for the good, that technology would solve problems, or that new resources could be discovered.

Technological fixes were pursued to seek ways to modify or control environmental change. 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 affected 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 (Krech, 1999: 45-72). 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 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 some of their settlements, as the Hohokam did, has yet to be determined (Colten, 2005; Steinberg, 2006; Vale and Campanella, 2005).

BOX 3.2: VIGNETTES OF VULNERABILITY - I

Alaskan Settlements

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 (ACIA, 2004). 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.

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).

Besides impacts on built infrastructures designed for permafrost foundations and effects on indigenous societies, 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).

Coastal Southeast Settlements

While there is currently no evidence for a long-term increase in North American mainland land-falling hurricanes, concerns remain that certain aspects of hurricanes, such as wind speed and rainfall rates may increase (CCSP, 2008). In addition, sea level rise is expected to increase storm surge levels (CCSP, 2008). Recent hurricanes striking the coast of the U.S. Southeast cannot be attributed clearly to climate change, but they suggest a range of possible impacts. As an extreme case, consider the example of Hurricane Katrina. 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 20th 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).

BOX 3.3: 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, and conflicts over water rights are likely 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-wild lands interface (Morehouse *et al.*, 2006). Drying would lengthen the fire season, and pest outbreaks such as the pine beetle could affect the scale of fires.

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.

BOX 3.4: 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 3.1) is affected by climate change, but overall, climate change is likely to impact the UHI effect in the following ways:

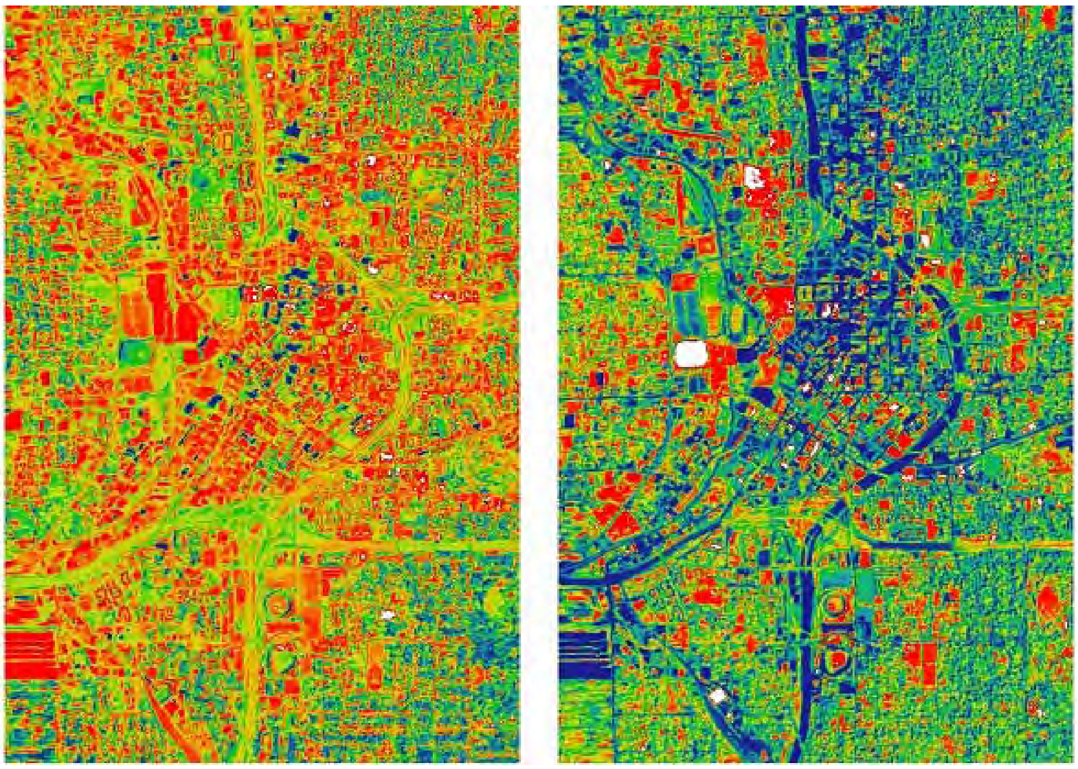


Figure 3.1. Example of urban surface temperatures and albedo for the Atlanta, Georgia Central Business District (CBD) area derived from high spatial resolution (10m) aircraft thermal remote sensing data. The image on the left illustrates daytime surface heating for urban surfaces across the CBD. White and red colors indicate very warm surfaces (~40-50°C). Green relates to surfaces of moderately warm temperatures (~25-30°C). Blue indicates cool surfaces (e.g., vegetation, shadows) (~15-20°C). 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 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 could 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 ($PM_{2.5}$) could increase due to a number of human induced and natural factors (e.g., more energy production to support higher usage of air conditioning).

- 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 would 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)

BOX 3.5: ROLES OF SETTLEMENTS IN CLIMATE CHANGE MITIGATION

Although U.S. government commitments to climate change mitigation policies at the national level have emerged only recently, an increasing number of state and local authorities are involved in strategies to mitigate greenhouse gas emissions (Selin and Vandeveer, 2005; Rabe, 2006; Selin, 2006). U.S. states and cities are joining such initiatives as ICLEI (ICLEI, 2006), the U.S. Mayor Climate Protection Agreement, the Climate Change Action Plan, the Regional Greenhouse Gas Initiative (RGGI) (Selin, 2006), and the Large Cities Climate Leadership Group.[1] These 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). These strategies, which mandate an increase in the amount of electricity generated from renewable resources also 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 efforts. Public and private entities 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 on 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 U.S. is considerable, 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/

3.8 Tables

Table 3.1. Overview of Integrated Assessments of Climate Impacts and Adaptation in U.S. Cities. "x" indicates that the reference addresses a category of interest.

	Bloomfield *et al.*, 1999	**Kooten *et al.*, 2001**	**Rosenzweig *et al.*, 2000**	**Kirshen *et al.*, 2004**	**Hoo and Sumitani, 2005**
Location:	Greater Los Angeles	New York	Metropolitan New York	Metropolitan Boston	Metropolitan Seattle
Coverage:					
Water supply	✓	✓	✓	✓	
Water Quality				✓	
Water Demand				✓	
Sea-level Rise	✓		✓	✓	✓
Transportation				✓	✓
Communication					
Energy			✓	✓	
Public Health					
Vector-borne Diseases					
Food-borne Diseases		✓			
Temperature-related Mortality				✓	
Temperature-related Morbidity	✓	✓			
Air-quality Related Mortality					
Air-quality Related Morbidity			✓		
Other Health Issues	✓	✓	✓		
Ecosystems					
Wetlands					
Other Ecol.(Wildfires)	✓		✓		
Urban Forests (Trees and Vegetation)		✓			
Air Quality		✓			✓
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	None	None	Low	Low	Low

Impacts (e.g., on individual types of businesses, populations)					

Table 3.2. 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; e.g., interactions between climate change and aging infrastructures	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; sea level rise	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, sea-level rise	Storm behavior, precipitation change

Synthesis and Assessment Product 4.6

Chapter 4

Effects of Global Change on Human Welfare

Lead Author: Frances G. Sussman, Environmental Economics Consulting

Contributing Authors: Maureen L. Cropper, University of Maryland at College Park, Hector Galbraith, Galbraith Environmental Sciences LLC, David Godschalk, University of North Carolina at Chapel Hill, John Loomis, Colorado State University, George Luber, Centers for Disease Control and Prevention, Michael McGeehin, Centers for Disease Control and Prevention, James E. Neumann, Industrial Economics, Incorporated, W. Douglass Shaw, Texas A&M University, Arnold Vedlitz, Texas A&M University, Sammy Zahran, Colorado State University

TABLE OF CONTENTS

4.1 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, well-being, and quality of life (terms that are often used interchangeably) refer to aspects of individual and group life that improve living conditions and reduce chances of injury, stress, and loss. The physical environment is one factor, among many, that may improve or reduce human well-being. Climate is one aspect of the physical environment, and can affect human well-being via economic, physical, psychological, and social pathways that influence individual perceptions of quality of life.

Climate change may result in lifestyle changes and adaptive behavior with both positive and negative implications for well-being. 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) changes in intra- and inter-country human migration patterns. More generally, studies of climate change and the United States identify an assortment of impacts on human health, the productivity of human and natural systems, and human settlements. Many of these impacts—ranging from changes in livelihoods to changes in water quality and supply—are linked to some aspect of human well-being.

Communities are also an integral determinant of human well-being. 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 well-being directly, for example, due to a lost job or a more difficult commute. In other cases, individual well-being may be indirectly affected, for example, due to concern for the well-being of other individuals, or for a lack of cohesion in the community. The sustainability or resilience of a community (i.e., its ability to cope with climate change and other stressors over the long term) may be reduced by climate change weakening the physical and social environment In the extreme, such changes may undermine the individual's sense of security or faith in government officials and government policies to accommodate change.

Completely cataloging the effects of global change on human well-being or welfare would be an immense undertaking. Despite its importance, no well-accepted structure for doing so has been developed and applied. Moreover, little (if any) research focuses explicitly on the impact of global change on human well-being, *per se*. The chapter seeks to make a review of this topic manageable by focusing on several discrete issues:

- Alternative approaches to defining and studying human well-being
- Identifying human well-being and quality of life measures and indicators (qualitative and quantitative)
- Describing economic welfare and monetary methods of assigning value to climate change's potential impacts

- Providing examples of climate change impacts on selected categories of well-being and reporting indicators of economic welfare for these categories

Section 4.2, focuses on valuation and non-monetary metrics and draws on the literature to provide insights into a possible foundation for future research into the effects of climate change on human well-being. This section first discusses the literature defining human well-being. 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 well-being 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 well-being that might be affected by climate change, and for making the identification of measures or metrics of well-being a more concrete enterprise in the future. To illustrate that potential, the section draws links between community welfare and some of the negative impacts of climate change.

Economics 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 4.3 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 fourth section of the chapter summarizes some of the key points of the chapter and the chapter concludes with a brief discussion of research gaps.

4.2 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, and they are all often used interchangeably (Veenhoven, 1988, 1996, 2000; Ng, 2003; Rahman 2007). Academic economists, epidemiologists, health scientists, psychologists, sociologists, geographers, political scientists, and urban planners have all rendered their own definitions and statistical indicators of life quality at both individual and community levels.[2] For purposes of clarity in this chapter, from this point forward we adopt the convention of the Millenium Assessment (MA 2005) and the Intergovernmental Panel on Climate Change (IPCC 2007b), which use "well-being" as an umbrella term—referring broadly to the extent to

[1] Because more concrete aspects of welfare, such as impacts on prices or income, may be covered by other synthesis and assessment products (see, for example, discussions of dollar values in SAP 4.3, *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity,* which is in draft form at the time this is being written), 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.

[2] For example, In sociological literature, the terms well-being and welfare are used interchangeably to refer to objectively measurable life chances and experiences, and the term quality of life is used to describe subjective assessments and experiences of individuals.

which human conditions satisfy the range of constituents of well-being, including health, social relations, material needs, security, and freedom of choice. "Quality of life" is here used synonymously with well-being, to reflect usage in a wide range of disciplines, including medical, sociological, psychological, and urban planning literatures. The term "welfare" is generally used herein to refer narrowly to economic measures of individual well-being, although it is also used in the context of communities in a broader sense.

Despite differences in definitions, human well-being—in its broadest sense—is typically a multi-dimensional concept, addressing the availability, distribution, and possession of economic assets, and non-economic goods 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 quantity 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).

The concepts of well-being, economic welfare, and quality of life play important roles not only in academic research, but also in practical analysis and policy making. Quality of life measures may be used, for example, to gauge progress in meeting policy or normative 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 life chances 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 Human Development Programme (UNDP) to the Milllenium Ecosystem Assessment on Ecosystems and Human Well-Being and highly regarded periodicals like *The Economist*, have built composite measures of human and societal well-being to compare and rank nations of the world.[4]

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

4.2.1 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 first, and then next to place-focused indicators.

[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.

[4] See, for example, the discussion of the sources of Table 1 subsequently in this chapter, which include a number of country-level quality of life assessments. The UNDP Human Development Index, a country by country ranking of quality of life indicators, can be accessed at http://hdr.undp.org/en/statistics/.

4.2.1.1 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 an individual's 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).

4.2.1.2 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 discover and quantify 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. Similarly, the scholarly literature notes 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. Cross-national analyses generally 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).[5] In such studies, subjective valuations of life satisfaction are embedded in broader conceptions of quality of life associated with the conditions of a geographic place, community, region or country—the social indicators approach.

4.2.2 The Social Indicators Approach

In this second strand of 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

[5]Some 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 or to conditions in their past. See, for example, Frank 1985.

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 well-being. 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 them to considerable debate and discussion. Second, they offer considerable breadth and flexibility in terms of categories of human well-being that can be included. Third, for many of the indicators or dimensions of well-being, objective metrics exist for measurement.

In addition, while its strength is in providing indicators of progress on individual dimensions of quality of life, the indicators approach has also been used to support aggregate or composite measures, at least for purposes of ranking or measuring progress. Various techniques are also available, or being developed, that aggregate or combine measures of well-being. These range from pure data reduction procedures to stakeholder input models where variables are evaluated on their level of social and economic importance. For example, Richard Florida (2002a) has constructed a statistical index of technology, talent, and social tolerance variables 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 relationships between human well-being and climate change.

4.2.2.1 A Taxonomy of Categories of Wellbeing

Taxonomies of place-specific well-being or 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. These categories represent broad aspects of personal and family circumstances, social structures, government, environment, and the economy that influence well-being. Table 4.1 illustrates these categories, which are listed in Column 1. The third column, "components/indicators of welfare" provides examples of the way in which these categories are often interpreted. These components represent what, in an ideal world, researchers would wish to measure in order to determine how a specific society fares from the perspective of well-being. The fourth column provides illustrative metrics, i.e., objective or quantifiable measures that are often used by researchers as indicators of well-being for each category.[6] Finally, the last column provides some examples of climate impacts that may be linked to that category. This column should not be viewed as an attempt to create a comprehensive list of impacts, or even to list impacts with equal weights, in terms of importance or likelihood of occurrence. Further, while

---

[6] Sources that contributed to the development of Table 1 include: MA (2005); Sufian, 1993; Rahman, *2007, and* Lambiri, *et al.*, 2007. 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 4.1 focuses on negative impacts (as potentially more troubling for quality of life), there are also opportunities or potential positive impacts that will result in some categories.

These categories of well-being or life quality are interrelated. For example, as economic or social conditions in a society improve (e.g., as measured by GDP per capita and rates of adult literacy), improvements occur in human health outcomes such as infant mortality, rates of morbidity, and female life expectancy at birth. Thus, while the categories and corresponding metrics of well-being presented in Table 4.1 are analytically separable, in reality they are highly interconnected.[7]

Economics as a source of quality of life 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 well-being refers to natural features, such as ecosystem services, 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 (Blomquist *et al.*, 1988; Glaeser *et al.*, 2001; Cheshire and Magrini, 2006).

Human health as a source of well-being includes features of a community, locality, 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 well-being include transportation, energy and communication technologies that enable commerce, mobility, and social connectivity. These technologies provide basic conditions for individual pursuits of well-being (Lambiri, *et al.*, 2007).

Government and public safety as a source of well-being are 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 well-being are conditions of life that promote social harmony, family and friendship, and the availability of arts, entertainment, and leisure activities that facilitate human happiness. The terms social and creative capital have

[7] More recently, scholars (Costanza *et al.* 2007) and government agencies (like NOAA's 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 to foster 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).

become 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).

In thinking about these indicators, it is important to keep two important contextual realities about climate change and well-being at the forefront. First, while discussions of climate change usually have a global resonance to them, the fact is that the effects of any specific changes in temperature, rainfall, storm frequency/intensity and sea level rise will be felt at the local and regional level by citizens and communities living and working in those vulnerable areas. Therefore, not all populations will be placed under equal amounts of climate change-generated stress. Some will experience greater impacts, will suffer greater damage, and will need more remediation and better plans and resource allocations for adaptation and recovery efforts to protect and restore quality of life (see, for example, Zahran *et al.*, 2008; Liu, Vedlitz and Alston, 2008; Vedlitz *et al.*, 2007).

Second, not all citizens in areas more vulnerable to climate change effects are equally at risk. Some population groupings, within the same community, will be more vulnerable and at risk than others. Those who are poorer, minorities, aged or infirmed, and children are at greater risk than others to the stresses of climate change events (Lindell and Perry, 2004; Peacock, 2003). Recognizing that not all citizens of a particular vulnerable area share the same level of risk is something that planners and decision makers must take into account in projecting the likely impacts of climate change events on their populations, and in dealing with recovery of those populations (Murphy and Gardoni, 2008).

Finally, the situation is further complicated as climate stressors negatively affect disease conditions in other nations with particularly vulnerable and mobile populations. Increased communicable disease incidence in developing nations have the potential, through legal and illegal tourism and immigration, to affect community welfare and individual well-being in the United States.

4.2.2.2 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 4.1—could provide information to 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 4.1 are intended to be illustrative of the types of indicators that might be used, rather than a comprehensive or recommended set. 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, or 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 4.1 is that social indicators provide a diverse and potentially rich perspective on human well-being.

The taxonomy presented in Table 4.1—or a similar taxonomy—might also provide a basis for analyses of the impacts of climate change on human well-being, 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.[8] At the least, different conditions and stakeholder mixes may demand different emphases. All taxonomies, however, face a common problem: how to interpret and use the diverse indicators, in order to compare and contrast alternative adaptive or mitigating responses to climate change. For some purposes, metrics have been developed that that aggregate across individuals or individual categories of well-being and present a composite measure of well-being; or otherwise operationalize related concepts, such as vulnerability (see, for example the discussion of Figure 4.1).

Figure 4.1 Geography of Climate Change Vulnerability at the County Scale

4.2.3 A Closer Look at Communities

Looking beyond well-being of individuals to the welfare (broadly speaking) of *communities*—networks of households, businesses, physical structures, and institutions—provides a broader perspective on the impacts of climate change. The categories and metrics in Table 4.1 are appealing from an analytical perspective in part because they represent dimensions of well-being 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 of 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 on different values; thus, 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 4.1 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 sectoral 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.

[8] 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).

4.2.3.1 Community Welfare and Individual Well-being

Rapid onset extreme weather 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 (see additional discussion in Chapter 3). 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, by extension, the analogous social indicators and metrics, consider a natural resource that faces additional stresses from 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 4.2 presents some of the possible pathways by which resource changes could affect diverse categories of quality of life; the purpose of Table 4.2 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. Table 4.2 illustrates the general principle of complex linkages in which a general equilibrium approach can be used to model climate change impacts.

4.2.3.2 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.[9] 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; Fagan, 2001; Ponting, 1991; Tainter, 1988). 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;

[9] Measures of quality of life provide a database of relevant individual 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.

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 on 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*. 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.

4.2.4 Vulnerable Populations, Communities, and Adaptation

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). Different groups within the community will be differentially vulnerable to climate changes, such as extreme events.

4.2.4.1 Vulnerable populations.

Categories of persons susceptible to environmental risks and hazards include racial and ethnic groups (Bolin 1986; Fothergill *et al.* 1999; Lindell and Perry 2004; Cutter 2006), and groups defined by economic variables of wealth, income, and poverty (Peacock 2003; Dash et al 1997; Fothergill and Peek 2004). Overall, research indicates that minorities and the poor are differentially harmed by disaster events. Economic disadvantage, lower human capital, limited access to social and political resources, and residential choices are social and economic reasons that contribute to observed differences in disaster vulnerability by race/ethnicity and economic status. While the literature on climate change and vulnerable populations is relatively underdeveloped, Chapter 2 on Human Health and Chapter 3 on Human Settlements each address population vulnerabilities.

Economic, social and health effects are not neatly bounded by geographic or political regions, and so the damage and stresses that occur in a specific locality are not limited in their effects to only that community. As Hurricane Katrina made clear, impacts felt in one community ripple throughout the region and nation. Persons made homeless in New Orleans resettled in Baton Rouge, Lafayette and Houston, creating stresses on those communities. Vulnerable groups migrate from stricken areas to more hospitable ones, taking their health, economic and educational needs and problems with them across both national and state lines

4.2.4.2 Vulnerable communities.

While most analyses of vulnerability tend to be conducted at the regional scale, Zahran *et al.* (2008) 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 4.1, in which darker areas represent higher vulnerability).

Many possible dimensions can be used to identify and measure vulnerabilities to climate change impacts and stressors. The one presented in Figure 4.1 illustrates that the concept of vulnerability is a viable one and can be measured and applied to communities in a GIS context. It is not the purpose of this chapter to focus in great detail on vulnerability measurement issues (for those interested in other formulations of the vulnerability concept, see Dietz *et al*., In Press).

4.2.4.3 Adaptation.

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. Thus, a resilient community 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 and demographic groups (Smit and Pilifosova, 2001).

Public policies and programs are in place in the U.S. to enhance the capacity of communities to mitigate[10] damage and loss from natural hazards and extreme events (Burby, 1998; Mileti, 1999; Godschalk, 2007). A considerable body of research looks at 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*., 2007). Research also has been done on the social vulnerability of communities to natural hazards (Cutter *et al.*, 2003) and the economic resilience of businesses 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.

4.3 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 4.2), 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 possible—approach to aggregation.[11]

[10] 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.)

[11] In part because of the difficulty in compiling the information needed for aggregation of economic measures, Jacoby (2004) 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.

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.

Fundamental to the economic 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. However, the economic approach, when interpreted as requiring a strict cost-benefit test, is not appropriate in all circumstances, and is viewed by some as controversial in the context of climate change.[12] Benefit cost analysis is 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 relevant. For example, the recent Synthesis Report of the IPCC Fourth Assessment (IPCC 2007a) presents an average social cost (i.e., damages) of carbon in 2005 of $12 per ton of CO_2, but also notes that the range of the roughly 100 peer-reviewed estimates of this value is -$3 to $95/t$CO_2$.[13] IPCC attributes this very broad range to differences in assumptions on climate sensitivity, response lags, the treatment of risk and equity, economic and non-economic impacts, the inclusion of potentially catastrophic losses, and discount rates. IPCC therefore suggests consideration of an "iterative risk management process" to support decision-making.[14] Estimated benefits and costs therefore can provide information relevant to decision makers, but some of the methodologies and data

[12] See Arrow *et al.*, 1996 - at page 7, "There may be factors other than economic benefits and costs that agencies will want to weigh in decisions, such as equity within and across generations. In addition, a decision maker may want to place greater weight on particular characteristics of a decision, such as potential irreversible consequences."
[13] See IPCC 2007a, page 23.
[14] IPCC further notes that existing analyses suggest costs and benefits of mitigation are roughly comparable in magnitude, "but do not as yet permit an unambiguous determination of an emissions pathway or stabilization level where benefits exceed costs." (IPCC 2007a page 23).

necessary to provide a relatively complete assessment may be unavailable, as discussed subsequently in this section.[15]

4.3.1 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 and income.[16] 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 Report to Congress completed by U.S. EPA in 1989 (USEPA 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 (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. One such comprehensive attempt generated a value for 17 ecosystem services from 16 ecosystem types (Costanza *et al.*, 1997), but also generated controversy and criticism from many

[15] Other factors that might be considered, in addition to economic estimates, include emotions, perceptions, cultural values, and other subjective factors, all of which can play a role in creating preferences and reaching decisions. Those factors are beyond what we can evaluate in this chapter.

[16] Although economists are careful to distinguish between the metrics of utility and money as distinct, valuation metric in dollar units (rather than units of utility) may be generally viewed as the outcomes of individual preference expressions among goods, income, and time.

economists (Bockstael *et al.*, 2000; Toman 1998; see National Research Council 2004 for a summary). Other analysts have attempted to define measures to reflect non-market ecosystem services in terms similar to those used for Gross Domestic Product (Boyd 2006), or indicators of ecosystem health that reflect ecological contributions to human welfare (Boyd and Banzhaf 2006).[17] While there are several well-done valuation analyses for non-market effects of climate change (as described later in this chapter), 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.

4.3.2 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 natural 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. Such effects 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

[17] Some political economists also emphasize the role of explicit recognition of non-market environmental values as an important step in improving the well-being of poor populations (Boyce and Shelley, 2003).

(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

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.

4.3.3 Human Health

In the US, climate change is likely to measurably affect health outcomes known to be associated with weather and climate, including heat-related illnesses and deaths , health effects due to storms, floods, and other extreme weather events, health effects related to poor air quality, 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 mental health, the ability to function physically (to climb stairs or walk a mile), socially (to move freely in the world), and in a work environment. Please see Chapter 2 of this report, which provides an overview of health effects that have been associated with climate change.

Despite our understanding of the pathways linking climate and health effects, there is uncertainty as to the magnitude and geographic and temporal variation of possible impacts on 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). Even where our understanding of underlying climate and health relationships is better, few studies have attempted to explicitly link these findings to climate change scenarios to quantitatively estimate health impacts. 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.

4.3.3.1 Overview of Health Effects of Climate Change

The US is a developed country with a temperate climate. It has a well-developed health infrastructure and government and non-governmental agencies involved in disaster planning and response, both of which can help to mitigate potential health effects from climate change. Nevertheless, certain regions of the US will face difficult challenges arising from some of the following health effects.

- *Illnesses and deaths due to heatwaves*—A likely impact in the US is an increase in the severity, duration, and frequency of heatwaves (Kalkstein and Greene 1997; IPCC 2007c). This, coupled with an aging (and therefore more vulnerable) population, will increase the likelihood of higher mortality from exposure to excessive heat (see, for example, Semenza *et al.*, 1996, and Knowlton *et al.*, 2007).
- *Injuries and death from extreme weather events*—Climate change is projected to alter the frequency, timing, intensity, and duration of extreme weather events, such as hurricanes and floods (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).
- *Illnesses and deaths due to poor air quality*—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, for ozone, compounded by assumptions of trends in precursor emissions. Despite these uncertainties, all else being equal, climate change is projected to increase ozone-related diseases.
- *Water- and Foodborne Diseases*—Altered weather patterns, including changes in precipitation, temperature, humidity, and water salinity, are likely to affect the distribution and prevalence of food- and waterborne diseases resulting from bacteria, 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 distinct seasonal pattern, suggesting that they may be sensitive to climate-driven changes in rainfall and

temperature (Githeko and Woodward, 2003). Moderating factors, such as housing quality, land-use patterns, vector control programs, and a robust public health infrastructure, are likely to prevent the large-scale spread of these diseases in the U.S.

4.3.3.2 Quantifying the Health Impacts of Climate Change

A large epidemiological literature exists on the health effects associated with climate change, particularly the mortality effects associated with increases in average monthly or seasonal temperature, and with changes in the intensity, frequency, and duration of heatwaves. As described in Chapter 2, there is considerable speculation concerning the balance of climate change-related decreases in winter mortality compared with increases in summer mortality, although researchers suspect that declines in winter mortality associated with climate change are unlikely to outweigh increases in summer mortality.

Net changes in mortality are difficult to estimate because, in part, much depends on complexities in the relationship between mortality and the changes associated with global change. Using average temperatures to estimate cold-related mortality, for example, is complicated by the fact that many factors contribute to winter mortality (such as spread of the influenza virus). Similarly, increased summer mortality may be affected not only by average temperature, but also by other temperature factors, such as variability in temperature, or the duration of heat waves. Moreover, quantifying projected temperature-related mortality requires going beyond epidemiology and (for example) projecting adaptive behaviors, such as the use of air conditioning, expanded public programs (such as heat warning systems), or migratory patterns.

Few studies have attempted to link the epidemiological findings to climate scenarios for the United States, and studies that have done so have focused on the effects of changes in average temperature, with mixed results.[18] Below, we report the results of these studies in order to give a sense of the magnitude of mortality that might be associated with temperature changes associated with climate change and, by intimation, the magnitude of potential changes in economic welfare. The conclusions should be considered preliminary, however, in part because of the complexities in estimating mortality under future climate scenarios. Moreover, none of the studies reported below traces through the quantitative implications of various climate scenarios for mortality in all regions of the United States using region-specific data, suggesting a clear need for future research.

Quantifying the relationship between climate change and cases of injury, illness, or death requires an exposure-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 exposure-response function can be used to compute the relative risk of illness or death due to a specified change in climate, e.g., a temperature increase of 2.5°C. Applying this relative risk to the baseline incidence of the illness

[18] To our knowledge, there have been no attempts to quantify the impacts of climate on cardiovascular and respiratory morbidity in the United States. 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. (DALYs represent the sum of life-years lost due to premature death and productive life years lost due to chronic illness or injury.) These impacts are estimated to be zero for the United States.

or death in a population yields an estimated number of cases associated with the climate scenario.

Two studies have attempted to link exposure-response functions to future climate scenarios and thereby develop temperature-related mortality estimates.[19] McMichael *et al.* (2004) estimate the effects of average temperature changes associated with projected climates resulting from alternative emissions scenarios, by WHO region. For the AMR-A region, which includes the United States, Canada, and Cuba, they estimate the impact on cardio-vascular mortality relative to baseline conditions in 1990. Effects are estimated for average temperature projections associated with three alternative emissions scenarios: (1) no control of GHG emissions,[20] (2) stabilization at 750 parts-per-million (ppm) of CO_2 equivalent by 2210, and (3) stabilization at 550 ppm CO_2 equivalent by 2170.[21]

McMichael *et al.* (2004) bases the estimates of the effects of average temperature changes on mortality from cardio-vascular disease (CVD) for AMR-A on Kunst *et al.* (1993). Kunst *et al.* (1993) find CVD mortality rates to be lowest at 16° C, and to increase by 0.5% for every degree C below 16° C and increase by 1.1% for each degree above 16° C. In applying these results to future climate scenarios, McMichael *et al.* (2004) assume that people will adjust to higher average temperatures; thus, the temperature at which mortality rates reach a minimum is adjusted by scenario. No adjustment is made for attempts to mitigate the effects of higher temperatures through (for example) increased use of air-conditioning. The effect of the climate scenarios for the North American region (AMR-A), reported for 2020 and 2030, is, on net, zero—reductions in CVD mortality due to warmer winter temperatures cancel out increases in CVD mortality due to warmer summer temperatures.

Hayhoe *et al.* (2004) examine the impacts on climate and health in California of projected climate change associated with two emissions scenarios. The emissions scenarios are similar to those used in McMichael *et al.* (2004): (1) stabilization at 970 ppm of CO_2 and (2) stabilization at 550 ppm of CO_2.[22] In Los Angeles, by the end of the century, the number of heatwave days (3 or more days with temperatures above 32 °C) increases fourfold under scenario B1 and six to eight times under scenario A1fi. From a baseline of 165 excess deaths in the 1990s, heat-related deaths in Los Angeles are projected to increase two to three times under scenario B1 and five to seven times under scenario A1fi by 2090.

These results can be compared with those of an earlier study that employed a composite climate variable to examine the impact of extreme temperatures on daily mortality under future climate scenarios. Kalkstein and Greene (1997) analyzed the effect of temperature extremes (both hot and cold) on mortality for 44 US cities in the summer and winter. They then applied these results to climate projections from two GCMs for 2020 and 2050. In 2020, under a no-control scenario,

[19] These studies use climate scenarios that are associated with different emissions scenarios from IPCC (2000), the so-called SRES scenarios.
[20] McMichael *et al.* (2004) represent unmitigated emissions using the IS92a emissions scenario presented in IPCC (2000).
[21] Climate scenarios are projected for 2025 and 2050 using the HadCM2 model at a resolution of 3.75° longitude by 2.5° latitude and interpolated to other years.
[22] Hayhoe uses two SRES (IPCC 2000) emissions scenarios: A1fi (corresponding to 970 ppm of CO_2) and B1 (corresponding to 550 ppm of CO_2).

excess summer deaths in the 44 cities were estimated to increase from 1,840 to 1,981-4,100, depending on the GCM used. The corresponding figures for 2050 were 3,190-4,748 excess deaths.

4.3.3.3 Valuation of Health Effects

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 job risks and that there be sufficient competition in labor markets for compensating wage differentials to emerge.[23]. 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.[24]

This challenge is compounded by the long-term nature of climate risks, which suggests that much of the premature mortality associated with higher temperatures will occur in the future. Indeed, McMichael *et al*. (2004) and Kalkstein and Greene (1997) estimate mortality based on climate effects around the years 2020 and 2050; Hayhoe *et al.* (2004) analyze impacts in 2070-2099.

---

[23] 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.

[24] 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

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, 2007) 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 factors may affect the economic value that would be attached to excess mortality estimates, such as those derived by Kalkstein and Greene (1997).

The potential 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 future climate scenarios. In addition to quantified estimates of mortality and morbidity, themselves indications of well-being and 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 4.3. 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. From a valuation perspective, we would expect changes in functional limitations (stiffness of joints, difficulty walking) not to be linked directly to climate or to weather, but rather to be instrumental in people's location decisions and, thus, reflected in wages and property values. The relationship between climate and wages and property values are discussed in the subsequent section on Amenity values.

4.3.4 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 4.4). 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.

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 4.2. 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 4.2 Steps from Climate Change to Economic Valuation of Ecosystem Services

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 very likely to have major adverse impacts on ecosystems (Peters and Lovejoy, 1992; Bachelet *et al.*, 2001; Lenihan *et al.*, 2006; Galbraith *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 may affect 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 (Box 4.1).

Another potential community effect of climate change is the facilitation of community penetration and degradation by invasive weeds that will replace more sensitive native species (Malcolm and Pitelka, 2000)

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 very likely that one result of this will be to accelerate current extinction rates, 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 (Root *et al.*, 2003; 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 very likely that some are due to climate change (Root *et al.*, 2003; 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; Root *et al.*, 2003; 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 very 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 are 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, probably vary between different types of wetland (e.g., beaver swamps vs. cattail stands), and may vary spatially and temporally.

4.3.4.1 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 4.4.

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. Value can arise even if a good or service is not explicitly consumed, or an ecosystem even experienced.[25] Thus, it can be difficult to define, much less to measure the value of changes in these non-market services. To value these services, economists typically use stated preference (direct valuation) methods, a method that can be used not only for non-market services, but also to value services in other

[25] Economists have devoted much effort to defining the source of non-market values of ecosystems, coining such terms as “use” and “non-use” value, consumption value, existence value, and invoking, as reasons why people care about ecosystesm, the moral philosophies inherent in terms such as stewardship, spiritual values, etc. (see for example, Freeman (2003).

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. As the discussions indicate, the treatment of climate change, *per se* has been very sparse. Moreover, the lack of studies reflects, in part, a need to develop analytical linkages between the physical effects of climate on ecosystems, the services valued by humans, and appropriate techniques to value changes of the types, and with the breadth, indicated by studies of the effects of global change on ecosystems.

4.3.5.2 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 Brown (2000) and Layton and Levine (2003) estimate total values for preventing Colorado (Rocky Mountain) forest loss due to climate change, based on data from the same stated choice or preference survey. The survey was conducted with Denver-area residents, who were expected to be familiar with forested regions in their nearby mountains. Respondents were given detailed information about climate change impacts on these forests, including changes in tree line elevation over both 60-year and 150- year time horizons, and asked to make choices between alternatives, allowing recovery of implied willingness to pay (WTP). Layton and Brown (2000) found WTP in the range 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 (2003) 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) designed and implemented several versions of stated preference studies that explored the impacts of wild bird (duck) loss due to either adverse agricultural practices, climate change, or both. The respondents consisted of Pennsylvania duck hunters, although the hypothetical ecosystem impacts occured in the Prairie Pothole region, which is in the northern Midwestern states and parts of Canada. The authors considered a hypothetical loss in duck populations, with a scenario that presented 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.

Although very few studies have valued climate change impacts on ecosystems, economists have conducted numerous studies (primarily using direct valuation methods) of ecosystem values in particular geographic locations, often focusing on charismatic species, or specific types of ecosystems, such as wetlands, in a particular location. In some cases, the estimated values are linked to specific services that the species or ecosystem provide, 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) consider 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.

4.3.4.3 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 their components, 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 ecosystem values, 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).

4.3.5 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 Tol, 2004); the jobs created by recreational tourism provide economic benefits not only to individuals but also to communities.[26] A number of studies have looked at the 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 visitation days or economic welfare. This section describes the results of this research into the impacts on several forms of recreation and reports the economic benefits and losses associated with these changes at the national level.

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 watcher, 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 their devotees. Many of these devotees of specialized outdoor recreation

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

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 4.3 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). Weather conditions are considered one of the four greatest factors influencing tourism visitation (Pileus Project, 2007). 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 4.3. 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, 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-dependent 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. 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; Scott, Jones and Konopek (2007). 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 recreational activities most obviously harmed by warmer climate are sports that require snow or cold temperatures, such as downhill and cross country skiing, snowmobiling, ice fishing, and snowshoeing. Reductions in visitor use (see, for example, the studies reported in Table 4.5) occur primarily from shorter season, particularly early in the year at such traditional times as Thanksgiving and Spring break. But with warmer temperatures, there is also less precipitation as snow and more as rain on snow, which contributes to a much shallower 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 hot 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 projected 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 quantitative studies look at effects of temperature change in Canadian recreation.[27] Scott and Jones (2005) project that the golf season in Banff, Canada could be extended by at least one week and up to eight weeks. The combined effect of warmer temperatures lengthening the golfing season, and the increasing the desirability of golfing during the existing season, together result in an increase in the rounds of golf played by between 50% and 86%. (Similar increases might be expected for golf in northern 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 projected 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 doubtful that snowmaking would 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 in some years.

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.

Indirect effects. 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 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-

[27] 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.

Hodgins and Colby, 2006) and at a representative set of ski areas in the U.S. (Loomis and Crespi, 1999).[28]

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 times 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 may not 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 projected to reduce coldwater trout fisheries (U.S. E.P.A., 1995; Ahn, *et a*l. 2000) as well as native and hatchery stocks of Chinook salmon in the Pacific Northwest (Anderson, *et al.* 1993). Given trout and Chinook salmon 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 projected 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 affect up to 25% of U.S. fishing days (Vaughan and Russell, 1982). This 25% loss may be an upper limit as some coldwater stream anglers may substitute to less affected coldwater lakes/reservoirs or switch to cool/warm-water species such as bass (U.S. E.P.A., 1995). Studies that better account for substitution effects, such as Ahn *et al.* (2000), indicate a 2-20% drop in benefits of trout fishing depending on the projected degrees of temperature increase which ranged from 1°C to 5°C.

---

[28] 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 ideal; 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.

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). In the near term, recreational forests 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. In the long term, however, several analyses suggest forest species composition and migration due as well as net increases in forest area due to carbon dioxide fertilization (Joyce, *et al.* 2001; Iverson and Matthews, 2007). Thus, eventually there may be a resurgence in forest recreation.

Saunders and Easley (2006) find that natural resources of many western National Parks, National Recreation Areas, and National Monuments 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.

4.3.5.1 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 visiting the beach or water skiing at reservoirs more frequently 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 well-being is the change 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[29] 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.

[29] 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.

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 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.

As discussed below, economists have available a number of well-studied and techniques to evaluate the impacts of climate change on at least some of the recreational service provided by ecosystems. However, only a few studies have looked explicitly at the effects of climate change on recreation in the US. More research is needed to understand the linkages between weather and recreation, and to extrapolate results to the range of recreational activities throughout the US.

Change 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 2.5°C and 5°C increases 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 climate change will increase participation in activities such as water-based recreation, and reduce participation in snow sports.

Table 4.5 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 sports 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.[30]

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

[30] 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.

regional regression equations to project beach use, and the response of reservoir recreation to climate change was analyzed using visitation at U.S. Army Corps of Engineers reservoirs.

For some of the recreational activities, the Loomis and Crespi study included indirect, as well as direct, effects. 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 projected 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 presented below provides one of the few examples. Other studies include Scott and Jones (2005), which focused on Banff National Park, Scott *et al.* (2006), which looked at snow skiing, Scott, *et al.* (2007), which focused on Waterton National Parks, and Pendleton and Mendelsohn (1998), which estimated values for fishing in the northeastern US.[31] 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.

Loomis and Crespi (1999) and Mendelsohn and Markowski (1999) estimate the overall net gain in visitor benefits, using the change in visitor days reported in Table 4.5 and estimated values of a visitation day reported in the literature. Loomis and Crespi (1999) adopt a disaggregated activity approach, and Mendelsohn and Markowski (1999) apply a state level approach.[32] Both of these studies find that temperature increases of 5°C and up result in increased benefits. However, as noted below, the case study of Rocky Mountain National Park suggests that extreme heat is likely (based on the model results) to cause these visitor benefits to decrease at some point.

[31] The three papers by Scott are discussed elsewhere in this paper. Pendleton and Mendelsohn use a random utility model of recreational fishing in the northeastern U.S. They find that, while catch rates of rainbow trout would decrease, catch rates of other trout and pan fish would increase. On net, recreational fishing benefits (under a climate scenario associated with a doubling of atmospheric CO_2 concentrations) are reduced in the state of New York, but there are offsetting gains in more northern states like Maine.

[32] As noted above, Mendelsohn and Markowski (1999) used state level regression modeling to estimate effects on all activities. In contrast, Loomis and Crespi (1999), used different regression models and different geographic scales for different recreation activities to take advantage of the more micro-level datasets available for beach and reservoir recreation.

Visitors are 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 lose, tourism.

Some adaptive responses can be expensive, and may be of limited effectiveness; such as snowmaking at night, which is often mentioned as an 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. Box 4.2 summarizes a case study of the impacts of climate change on Rocky Mountain National Park.

4.3.6 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. We would also expect based on the evidence that, in addition to preferring certain temperatures and more sunshine, people would prefer 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.

4.3.6.1 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.[33] 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

[33] 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.

mean annual temperature would be worth between $30 and $100 billion (1987$) assuming that precipitation and seasonal variation in temperature remain unchanged.

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 suggest that warming produces 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.

4.3.6.2 Valuing Hurricanes, Floods, 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, for example, to disentangle 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, Florida, a county that did not suffer damage from the hurricane, to determine the impact of people's *perceptions* 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.

4.4 Conclusions

The study of the impacts of climate change on human welfare, well-being, and quality of life, is still developing. Many studies of impacts on particular sectors—such as health or agriculture—discuss, and in some cases quantify, effects that have clear implications for welfare. 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 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 is available for categorizing effects on quality of life, well-being, or human welfare. 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.

This chapter explores one commonly used method: the social indicators approach. This approach generally divides life quality effects into broad categories, such as economic conditions or human health, and then identifies subcategories of important effects.

Most of the measures of well-being—including the social indicators approach—focus on individual measures of well-being, although measured at the society level. There is, however, another dimension to well-being—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 well-being and quality of life.

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 well-being, and then valuing those effects using economic techniques.

Regardless of the framework, estimating impacts on human well-being 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 well-being or other metrics that can be used for policy purposes.

4.5 Expanding the Knowledge Base

Despite the potential for impacts on human well-being, little research focuses directly on understanding the relationship between well-being and climate change. Completely cataloging the effects of global change on human well-being or welfare would be an immense undertaking, and no well-accepted structure for doing so has been developed and applied. 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 may includes changes that are not easily captured by objective measures of well-being or quality of life.

This chapter has looked at the climate impacts and economics literature in four areas of welfare effects—human health, ecosystems, recreation, and climate amenities. For each of the non-market effects analyzed here, significant data gaps exist at each of the steps necessary to provide monetized values of climate impacts. Although the economics literature for only a few areas of effects is examined, it is probable that similar information gaps exist for the valuation of other impacts of climate change, particularly those that involve non-market effects (see Table 4.1). In addition, economic welfare—as with any other aggregative approach—does not adequately address the question of how to deal with effects which may not be amenable to valuation or with interdependencies among effects and systems.

Developing an understanding of the impacts of climate change on human welfare may require taking the following steps:

- Develop a framework for addressing individual and community welfare and well-being, including defining welfare/well-being for climate analysis and systematically categorizing and identifying impacts on welfare/well-being
- Identify priority categories for data collection and research, in order to establish and quantify the linkage from climate to welfare effects
- Decide which metrics should be used for these categories; more generally, which components of welfare/well-being should be measured in natural or physical units, and which should be monetized
- Investigate methods by which diverse metrics can be aggregated into a synthetic indicator (e.g., vulnerability to climate change impacts, including drought, sea level rise, etc.), or at least weighted and compared in policy decisions where aggregation is impossible
- Develop an approach for addressing those welfare effects that are difficult to look at in a piecemeal way, such as welfare changes on communities or ecosystems.
- Identify appropriate top-down and bottom-up approaches for estimating impacts and value (whether economic or otherwise) of the most critical welfare categories.
- Identify situations in which evaluation following the above steps is likely to be prohibitively difficult, and determining alternative methods for approaching the topic of the impact of global change on well-being.

Together, these steps should enable researchers to make progress towards promoting the consistency and coordination in analyses of welfare/well-being that will facilitate developing the body of research necessary to analyze impacts on human welfare, well-being, and quality of life.

4.6 References

Ahn, S., J. deSteiguer, R. Palmquist and T. Holmes. 2000. Economic analysis of the potential impact of climate change on recreational trout fishing in the Southern Appalachian Mountains. *Climatic Change* **45**: 493-509.

Alberini, Anna, Maureen Cropper, Alan Krupnick, and Natalie Simon, 2004: Does the value of a statistical life vary with age and health status? Evidence from the U.S. & Canada. *Journal of Environmental Economics and Management*, **48(1),** 769-792.

Anderson, D., S. Shankle, M. Scott, D. Neitzel and J. Chatters. 1993. Valuing effects of climate change and fishery enhancement on Chinook salmon. *Contemporary Policy Issues 11(4):82-94.*

Arrow, K.J., M.L. Cropper, G.C. Eads, R.W. Hahn, L.B. Lave, R.G. Noll, P.R. Portney, M. Russell, R. Schmalensee, V.K. Smith, and R.N. Stavins. 1996: *Benefit-Cost Analysis in Environmental, Health, and Safety Regulation: A Statement of Principles*. American Enterprise Institute, The Annapolis Center, and Resources for the Future, Washington, DC. Available at: http://aei-brookings.org/admin/authorpdfs/redirect-safely.php?fname=../pdffiles/arrow_cropper_etal.pdf

Bachelet, D., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2001: Climate change effects on vegetation distribution and carbon budget in the U.S. *Ecosystems*, **4,** 164-185.

Banuri, T., and J. Weyant, 2001: Chapter 1, Setting the stage: Climate change and sustainable development, in climate change 2001. *Contributions of Working Group III – Mitigation to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Bark-Hodgins, R. and B. Colby, 2006: Snow days? Using climate forecasts to better manage climate variability in the ski industry. Presentation at NOAA Climate Prediction Applications Science Workshop, held March 21-24 in Tucson, Arizona. Available at *http://cals.arizona.edu/climate/CPASW2006/proc/day4/EconomicsForecastValue/Bark.pdf*

Bayer, Patrick and Christopher Timmins, 2005: On the equilibrium properties of locational sorting models. *Journal of Urban Economics*, **57(3),** 462-77.

Bayer, Patrick, Nat Keohane and Christopher Timmins, 2006: *Migration and Hedonic Valuation: The Case of Air Quality*. NBER Working Paper #12106. To purchase, see http://www.nber.org/papers/w12106

Beebee, T.J.C, 1995: Amphibian breeding and climate. *Nature,* **374,** 219.

Berke, P., D. Godschalk, and E. Kaiser, 2006: *Urban Land Use Planning*. University of Illinois Press, Urbana, IL.

Bin, Okmyung and Stephen Polasky, 2004: Effects of flood hazards on property values: Evidence before and after Hurricane Floyd. *Land Economics,* **80(4),** 490-500.

Bishop, R., 1982: Option value: An exposition and extension. *Land Economics,* **58(1),** 1-15.

Black, Dan A., Jose Galdo, and Liqun Liu, 2003: *How Robust Are Hedonic Wage Estimates of the Price of Risk?* Final Report to the U.S. Environmental Protection Agency [R 829-43-001].

Blomquist, Glenn C., Mark C. Berger, and John P. Hoehn, 1988: New estimates of quality of life in urban areas. *American Economic Review,* **78(1),** 89-107.

Bockstael, Nancy E., A.M. Freeman, Raymond Kopp, Paul Portney, and V. Kerry Smith, 2000: On measuring economic values for nature. *Environmental Science and Technology,* **34(8),** 1384-90.

Bolin, R. (1986) ‘Disaster Impact and Recovery: A Comparison of Black and White Victims’. *International Journal of Mass Emergencies and Disasters (IJMED).* 4. pp. 35-50.

Both, C., Bouwhuis S., Lessells C.M., and Visser M.W., 2006: Climate change and population declines in a long-distance migratory bird. *Nature,* **441,** 81.

Bowling, A., 1997: *Measuring Health: A Review of Quality of Life Measurement Scales*. Open University Press, Philadelphia, PA, 2nd ed.

Boyce, J. and B. Shelley, 2003: *Natural Assets: Democratizing Environmental Ownership.* Island Press, Washington, DC.

Boyd, J., 2006: *The Nonmarket Benefits of Nature: What Should Be Counted in Green GDP?* Resources for the Future Discussion Paper RFF DP 06-24, May 2006.

Boyd, J. and S. Banzhaf, 2006: *What Are Ecosystem Services? The Need for Standardized Environmental Accounting Units*. Resources for the Future Discussion Paper RFF DP 06-02, January 2006.

Brown, J.L., S.H. Li, and N. Bhagabati, 1999: *Long-Term Trend Toward Earlier Breeding in an American Bird: A Response to Global Warming?* Proceedings of the National Academy of Sciences, USA **96,** pp. 5565–5569.

Burby, R. (ed.), 1998: *Cooperating with Nature: Confronting Natural Hazards with Land Use Planning for Sustainable Communities*. Joseph Henry Press, Washington, DC.

Campbell, S., 1996: Green cities, growing cities, just cities? Urban planning contradictions of sustainable development. *Journal of the American Planning Association,* **62,** 296-312.

Cheshire, P. and S. Magrini, 2006: Population growth in European cities: Weather matters – but only nationally. *Regional Studies,* **40(1),** 23-37.

Cline, W.R., 1992: *The Economics of Global Warming.* Institute for International Economics, Washington DC.

Coleman, J.S., 1988; Social capital in the creation of human capital, *American Journal of Sociology Supplement*, **94,** S95-S120.

Coleman, J.S., 1990; *Foundations of Social Theory*. Harvard University Press.

Coleman, J.S., 1993; The rational reconstruction of society, *American Sociological Review*, **58,** 1-15.

Cordell, H.K., B. McDonald, R.J. Teasley, J.C. Bergstrom, J. Martin, J. Bason, and V.R. Leeworthy, 1999: Outdoor recreation participation trends. In: *Outdoor Recreation in American Life: A National Assessment of Demand and Supply Trends.* Sagamore Publishing, Champaign, IL, pp. 449.

Costanza, R., R. d'Arge, R. deGroot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. O'Neill, J. Paruelo, r.g. Raskin, P. Sutton, M. van den Belt, 1997: The value of the world's ecosystem services and natural capital. *Nature,* **387,** 253-255.

Costanza, R., B. Fisher, S. Ali, C. Beer, L. Bond, R. Boumans, N. Danigelis, J. Dickinson, C. Elliott, J. Farley, D.E. Gayer, L.M. Glenn, T. Hudspeth, D. Mahoney, L. McCahill, B. McIntosh, B. Reed, S. Abu Turab Rizvi, D.M. Rizzo, T. Simpatico, and R. Snapp, 2007: Quality of life: An approach integrating opportunities, human needs, and subjective well-being. *Ecological Economics*, **61**, 267-276.

Cragg, M. and M. Kahn, 1997: New estimates of climate demand: Evidence from location choice. *Journal of Urban Economics,* **42(2),** 261-284.

Crick, H.Q.P., C. Dudley, D.E. Glue, and D.L. Thompson, 1997: UK birds are laying eggs earlier. *Nature*, **388,** 526.

Cropper, M.L. and A.S. Arriaga-Salinas, 1980: Inter-city wage differentials and the value of air quality. *Journal of Urban Economics,* **8(2),** 236-254.

Cropper, M.L., 1981: The value of urban amenities. *Journal of Regional Science,* **21(3),** 359-374.

Cropper, M.L. and F. G. Sussman, 1990: Valuing future risks to life. *Journal of Environmental Economics and Management*, **19(2),** 160-174.

Curriero, F., J. Patz, J. Rose, and S. Lele, 2001: Analysis of the association between extreme precipitation and waterborne disease outbreaks in the United States: 1948-1994. *American Journal of Public Health,* **91(8),** 1194-1199.

Curriero, F.C., J.M. Samet, and S.L. Zeger, 2003: Re:"on the use of generalized additive models in time-series studies of air pollution and health" and" temperature and mortality in 11 cities of the eastern United States". *American Journal of Epidemiology*, **158(1)**, 93-94.

Curriero, F.C., K.S. Heiner, J.M. Samet, S.L. Zeger, L. Strug, and J. Patz, 2002: Temperature and mortality in 11 cities of the eastern United States. *American Journal of Epidemiology*, **155(1)**, 80-87.

Cutter, S. (2006). The geography of social vulnerability: Race, class, and catastrophe, *Understanding Katrina: Perspectives from the Social Sciences*. http://understandingkatrina.ssrc.org/Cutter/

Cutter, S., B. Boruff, and W. Shirley, 2003: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84(1),** 242-261.

Daily, G.C., 1997: *Nature's Services. Societal Dependence on Natural Ecosystems*. Island Press, Washington, DC.

DeFreitas, C.R., 2005: The climate-tourism relationship and its relevance to climate change impact assessment. In: *Tourism, Recreation and Climate Change*. [Hall, C.M. and J. Higham (eds.)]. Channel View Publications, Buffalo, NY, pp. 29-43.

Diamond, J., 2005: *Collapse: How Societies Choose to Fail or Succeed*. Viking, New York, NY.

Diamond, P.A. and J. A. Hausman, 1993: On Contingent Valuation Measurement of Nonuse Values. In: *Contingent Valuation: A Critical Assessment* [Hausman, J.A. (ed.)]. North-Holland, Amsterdam, Netherlands.

Diener, E. and C. Diener, 1995: The wealth of nations revisited: Income and quality of life. *Social Indicators Research*, **36,** 275–286.

Diener, E., M. Diener, and C. Diener, 1995: Factors predicting the subjective well-being of nations. *Journal of Personality and Social Psychology,* **69(5),** 851–864.

Dietz, T., E. Al Rosa, & R. York, In Press. Human Driving Forces of Global Change: Examining Current Theories. In E. A. Rosa, A. Diekmann, T. Dietz & C. Jaeger (Eds.), Human Dimensions of Global Change (In press). Cambridge, Massachusetts, MIT Press. Available at http://www.stirpat.org/

Dunn, P.O., and D.W. Winkler, 1999: *Climate Change has Affected the Breeding Date of Tree Swallows Throughout North America.* Proceedings of the Royal Society of London, Series B, **266,** pp. 2487–2490.

Ehrlich, P. and A. Ehrlich, 1996: *Betrayal of Science and Reason.* Island Press, Washington DC.

Fagan, B., 2001: *The Little Ice Age*. Basic Books, New York, NY.

Frank, R.H., 1985. *Choosing the Right Pond*. Oxford: Oxford University Press.

Florida, R., 2002a: The economic geography of talent. *Annals of the Association of American Geographers* **92 (4),** 743–755.

Florida, R., 2002b: *The Rise of the Creative Class. And How It's Transforming Work, Leisure and Everyday Life*. Basic Books.

Fowler, A.M., and K.J. Hennessey, 1995: Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards,* **11,** 283-303.

Fankhauser, S., 1995: *Valuing Climate Change – The Economics of the Greenhouse*. EarthScan, London, UK.

Fothergill, A., E. G. M. Maestas, and J. D. Darlington (1999) 'Race, Ethnicity, and Disasters in the United States: A Review of the Literature'. *Disasters.* 23(3). pp.156-173.

Fothergill, A. and L. A. Peek (2004) 'Poverty and Disasters in the United States: A Review of Recent Sociological Findings'. *Natural Hazards.* 32. pp. 89-110.

Freeman, A.M., 2003: *The Measurement of Environmental and Resource Values: Theory and Methods*. Resources for the Future, Washington, DC, 2nd ed.

Frey, B.S. and A. Stutzer, 2002: *Happiness and Economics.* Princeton University Press, Princeton, NJ.

Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page, 2002: Global climate change and sea-level rise: potential losses of intertidal habitat for shorebirds. *Waterbirds*, **25,** 173–183.

Galbraith, H., J.B. Smith, and R. Jones, 2006. Biodiversity changes and adaptation. In: *The Impact of Climate Change on Regional Systems: a Comprehensive Analysis of California*, edited by J. B. Smith and R. Mendelsohn. Edward Elgar, Northampton, MA.

Githeko, A.K, and A. Woodward, 2003: International consensus on the science of climate and health: the IPCC Third Assessment Report. In: *Climate Change and Human Health: Risks and Responses* [A.J. McMichael *et al.* (eds.)]. WHO/WMO/UNEP, Geneva.

Glaeser, E.L., J. Kolko, and A. Saiz, 2001: Consumer city. *Journal of Economic Geography*, **1(1),** pp.27-51.

Glick, P. and Clough, J., 2006: *An Unfavorable Tide: Global Warming, Coastal Habitats and Sportfishing in Florida.* National Wildlife Federation, Washington, DC.

Godschalk, D.R., 2007: Mitigation. In: *Emergency Management: Principles and Practice for Local Government.* Second edition. [Waugh, W.L., Jr., and K. Tierney (eds)]. International City/County Management Association, Washington. DC, pp 89-112.

Godschalk, D.R., 2003: Natural hazard mitigation: Creating resilient cities. *Natural Hazards Review,* **4(3),** 136-143.

Graves, P.E. and P.R. Mueser, 1993: The role of equilibrium and disequilibrium in modeling regional growth and decline: A critical reassessment. *Journal of Regional Science,* **33(1),** 69-84.

Greenwood, M., G. Hunt, D. Rickman, and G. Treyz, 1991: Migration, regional equilibrium, and the estimation of compensating differentials. *American Economic Review,* **81(5),** 1382-1390.

Guyatt, G. H., D.H. Feeny, and D.L. Patrick, 1993: Measuring health-related quality of life. *Annals of Internal Medicine*. **118(8),** 622-629.

Gyourko, Joseph and Joseph Tracy, 1991: The structure of local public finance and the quality of life. *Journal of Political Economy,* **99(4),** 774-806.

Hall, C.M. and J. Highman, 2005: Introduction: Tourism, recreation, climate change. In: *Tourism, Recreation and Climate Change*. [Hall, C.M. and J. Higham (eds.)]. Channel View Publications, Buffalo, NY, pp. 3-28.

Hallstrom, D. and V.K. Smith, 2005: Market responses to hurricanes. *Journal of Environmental Economics and Management,* **50(3),** 541-61.

Hamilton, J. and R. Tol, 2004: *The impact of climate change on tourism and recreation.* FNU-52 Working paper, Research Unit Sustainability and Global Change, University of Hamburg, Germany. Purchase at http://ideas.repec.org/p/sgc/wpaper/52.html

Hamilton, J. and R. Tol. 2007. The impact of climate change on tourism in Germany, the UK and Ireland. *Regional Environmental Change. Published online July 25, 2007. http://www.springerlink.com/content/055v517726lm5u52/fulltext.html#CR10*

Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K.N. Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalkstein, J. Lenihan, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Verville, 2004: Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences of the United States of America,* **101(34)**, 12422-12427.

Health Care Financing Review (HCFR), 2004: *Special Issue on the Health Outcomes Survey.* **25(4),** 1-119.

Hersteinsson, P. and D.W. Macdonald, 1992: Interspecific competition and the geographical distribution of red and arctic foxes, *Vulpes vulpes* and *Alopex lagopus*. *Oikos,* **64,** 505–515.

Hoch, Irving and Judith Drake, 1974: Wages, climate, and the quality of life. *Journal of Environmental Economics and Management,* **1,** 268-296.

Holbrook, S.J., R.J. Schmitt, and J.S. Stephens, 1997: Changes in an assemblage of temperate reef fishes associated with a climatic shift. *Ecological Applications,* **7,** 1299-1310.

IPCC, 2007a: *Climate Change 2007: Summary for Policymakers of the Synthesis Report of the IPCC Fourth Assessment Report.* Draft Copy 16 November 2007.

IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Appendix I: glossary. http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-app.pdf

IPCC, 2007c: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B., Averyt, M. Tignor and h.L.Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2000: Special Report on Emissions Scenarios, Coordinating Lead Author: Nebojsa Nakicenovic. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 1996: *Climate Change 1995: Economic and Social Dimensions of Climate Change.* Second Assessment Report of the Intergovernmental Panel on Climate Change [Bruce, J., H. Lee, and E. Haites (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Irland, L., D. Adams, R. Alig, C. Betz, C.Chen, M. Hutchins, B. McCarl, K. Skog, and B. Sohngen, 2001: Assessing socioeconomic impacts of climate change on U.S. forests, wood-product markets, and forest recreation. *BioScience,* **51(9),** 753-764.

Iverson, L. and S. Matthews. 2007. Potential Changes in Suitable Habitat for 134 Tree Species in Northeastern United States. Available at http://www.northeastclimateimpacts.org/pdf/miti/iverson_et_al.pdf

Jacoby, Henry D., 2004: *Informing climate policy given incommensurable benefits estimates. Global Environmental Change Part A,* **14(3)**, 287-297

Joyce, L., J. Aber, S.McNulty, V. Dale, A. Hansen, L. Irland, R. Nelson and K. Skog. 2001. Potential Consequences of Climate Variability and Change for the Forests of the United States. In *Climate Change Impacts on the United States*. U.S. Global Change Research Program. Washington DC. Available at http://www.usgcrp.gov/usgcrp/nacc/forests/default.htm

Kahneman, D., E. Diener, and N. Schwarz (eds.), 1999: *Well-Being: The Foundations of Hedonic Psychology*. Russel Sage Foundation New York.

Kahneman, D. and A.B. Krueger, 2006: Developments in the measurement of subjective well-being. *Journal of Economic Perspectives,* **20(1),** 3-24.

Kalkstein, L.S. and Greene J.S., 1997: An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change. *Environmental Health Perspectives,* **105(1),** 84-93.

Kalkstein, L.S., 1989: The impact of CO2 and trace gas-induced climate changes upon human mortality. In: *The Potential Effects of Global Climate Change in the United States* [Smith, J. B. and D. A. Tirpak (eds.)]. Document no. 230-05-89-057, Appendix G, U.S. Environmental Protection Agency, Washington, DC.

Kalkstein, L.S. and R. E. Davis, 1989: Weather and human mortality: An evaluation of demographic and interregional responses in the United States. *Annals of the Association of American Geographers,* **79(1),** 44-64.

Kinnell, Jason, J.K. Lazo, D.j. Epp, A. Fisher, J.S. Shortle, 2002: Perceptions and values for preventing ecosystem change: Pennsyvlania duck hunters and the prairie pothole region. *Land Economics,* **78(2),** 228-244.

Knowlton, K., B. Lynn, R. Goldberg, C. Rosenzweig, C. Hogrefe, J. K. Rosenthal and P. L. Kinney, 2007. Projecting heat-related mortality impacts under a changing climate in the New York City region. *American Journal of Public Health*, **97(11)**, 2028-2034.

Kunst, A.E., C.W.N. Looman, and J. P. Mackenbach, 1993: Outdoor air temperature and mortality in the Netherlands: A time series analysis. *American Journal of Epidemiology,* **137(3),** 331-41.

Lambiri, Dionysia, Bianca Biagi, and Vincente Royuela. 2007. Quality of Life in the Economic and Urban Economic Literature. *Social Indicators Research*, **84(1)**, 1-25.

Layton, D. and G. Brown, 2000: Heterogeneous preferences regarding global climate change. *Review of Economics and Statistics,* **82(4),** 616-624.

Layton, David F. and Richard Levine, 2003: *How much does the future matter? A hierarchical Bayesian analysis of the public's willingness to mitigate ecological impacts of climate change.* Journal of the American Statistical Association 98(463): 533-544.

Lenihan, J.M., R. Drapek, and R. Neilson, 2006: Terrestrial ecosystem changes. In: *The Impact of Climate Change on Regional Systems. A Comprehensive Analysis of California*. [J.B. Smith and R. Mendelsohn (eds.)]. Edward Elgar, Northampton, MA.

Lindell, M. K., and R. W. Perry (2004) *Communicating Environmental Risk in Multiethnic Communities*. Sage, Thousand Oaks.

Lipp, E.K. and J.B. Rose, 1997: The role of seafood in foodborne diseases in the United States of America. *Revue Scientifique et Technique,* **16,** 620-640.

Liu, X., Vedlitz, A. and L. Alston. 2008. Regional News Portrayals of Global Warming and Climate Change. *Environmental Science and Policy* advance online publication, doi:10.1016/j.envsci.2008.01.002 [published online 4 March 2008].

Loomis, J. and R. Richardson, 2006: An external validity test of intended behavior: Comparing revealed preference and intended visitation in response to climate change. *Journal of Environmental Planning and Management,* **49(4),** 621-630.

Loomis, J., P. Kent, L. Stange, K. Fausch, and A. Covich, 2000: Measuring the total economic value of restoring ecosystem services in an impaired river basin: Results from a contingent valuation survey. *Ecological Economics,* **33,** 103-117.

Loomis, J. and J. Crespi, 1999: Estimated effects of climate change on selected outdoor recreation activities in the United States. In: *The Impact of Climate Change on the United States Economy* [Mendelsohn, R. and J. Neumann (eds.)]. Cambridge University Press, Cambridge, UK, pp. 289-314.

MA, 2005: *Millennium Ecosystem Assessment: Ecosystems and Human Well-being – Synthesis*. Island Press, Washington, DC.

MacKenzie W.R., W.L. Schell, K.A. Blair, D.G. Addiss,, D.E. Peterson, N.J. Hoxie, J.J. Kazmierczak, and J.P. Davis, 1994: A massive outbreak in Milwaukee of cryptosporidium infection transmitted through the public water supply. *New England Journal of Medicine,* **331(3),** 161-167.

MacMillan, D., E.I. Duff, and D. Elston, 2001: Modelling the non-market environmental costs and benefits of biodiversity projects. *Environmental and Resource Economics,* **18,** 391-401.

Malcolm, J.R., and L.F. Pitelka. 2000. *Ecosystems and Global Climate Change*. Pew Center on Global Climate Change, Washington, DC.

Martens, W.J.M., 1998: Climate change, thermal stress and mortality changes. *Social Science and Medicine*, **46(3),** 331-344.

McMichael, A.J., D. Campbell-Lendrum, R.S. Kovats, S. Edwards, P. Wilkinson, N. Edmonds, N. Nicholls, S. Hales, F.C. Tanser, D. Le Sueur, M. Schlesinger, and N. Andronova, 2004: Global Climate Change. In: *Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factor: Volume 2* [Ezzati M., A. Rodgers, and C. J. Murray (eds.)]. World Health Organization, Geneva, pp. 1543–1649.

McMichael, A.J. and A. Githeko, 2001: Human Health. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. [McCarthy, James J., Osvaldo F. Canziani, Neil A. Leary, David J. Dokken and Kasey S. White (eds.)]. Intergovernmental Panel on Climate Change - IPCC Working Group II, Cambridge University Press, Cambridge, pp. 453-485.

Melillo, J., A. Janetos, D. Schimel, and T. Kittel, 2001: Vegetation and Biogeochemical scenarios. In, *Climate Change Impacts on the United States. The Potential Consequences of Climate Variability and Change*. Report for the US Global Change Research Program, Cambridge University Press, Cambridge, UK.

Mendelsohn, R., 2001: A hedonic study of the non-market impacts of global warming in the US. In: *The Amenity Value of the Global Climate* [Maddison, D. (ed.)]. Earthscan, London, pp. 93-105.

Mendelsohn, R. and J.E. Neumann, 1999: *The Impact of Climate Change on the United States Economy*. Cambridge University Press, Cambridge, UK.

Mendelsohn, R. and M. Markowski, 1999: The impact of climate change on outdoor recreation. In: *The Impact of Climate Change on the United States Economy* [Mendelsohn, R. and J. Neumann (eds.)]. Cambridge University Press, Cambridge, UK, pp. 267-288.

Meyer, J.L., M.J. Sale, P.J. Mulholland, and N.L. Poff, 1999: Impacts of climate change on aquatic ecosystem functioning and health. In: *Potential Consequences of Climate Variability and Change to Water Resources of the United States* [D.B. Adams (ed).]. Conference papers 10-12 May 1999, Atlanta, GA.

Mileti, D.S., 1999: *Disasters by design: A reassessment of natural hazards in the United States*. Joseph Henry Press, Washington, DC.

Moore, T., 1998: Health and amenity effects of global warming. *Economic Inquiry*, **36(3),** 471–488.

Morris, M. (ed.), 2006: *Integrating Planning and Public Health: Tools and Strategies to Create Healthy Places*. American Planning Association, Washington, DC.

Morris, R.E., M.S. Gery, M.K. Liu, G.E. Moore, C. Daly, and S.M. Greenfield, 1989: Sensitivity of a regional oxidant model to variations in climate parameters. In: *The Potential Effects of Global Climate Change on the United States* [J.B.Smith and D.A.Tirpak (eds.)]. U.S. EPA, Office of Policy, Planning and Evaluation, Washington, DC.

Multihazard Mitigation Council, 2005: *Natural hazard mitigation saves: An independent study to assess the future savings from mitigation activities*. National Institute of Building Sciences, Washington, DC.

Murphy, Coleen and P. Gardoni. 2008. The Acceptability and the Tolerability of Societal Risks: A Capabilities-based Approach. *Science and Engineering Ethics*, **14(1)**, 77-92.

National Research Council, Committee on Assessing and Valuing the the Services of Aquatic and Related Terrestrial Ecosystems, 2004: *Valuing Ecosystem Services: Toward Better Environmental Decision-Making.* The National Academies Press, Washington, DC.

Ng, Y.K., 2003: From preferences to happiness: toward a more complete welfare economics. *Social Choice and Welfare,* **20,** 307-350.

Nordhaus, William and Joseph Boyer, 2000: *Warming the World: Economic Modeling of Global Warming.* MIT Press, Cambridge, MA.

Nordhaus, William, 1994: *Managing the Global Commons: The Economics of Climate Change.* MIT Press, Cambridge, MA.

Northbridge, M., E. Sclar, and P. Biswas, 2003: Sorting the connections between built environment and health: A conceptual framework for navigating pathways and planning healthy cities. *Journal of Urban Health,* **80(4),** 556-568.

Oechel, W.C., S.J. Hastings, G. Vourlitis, and M. Jenkins, 1993: Recent change of arctic tundra ecosystems from net carbon dioxide sink to a source. *Nature,* **361,** 520-523.

Oechel, W.C., G.L. Vourlitis, S.J. Hastings, R.C. Zulueta, L. Hinzman, and D. Kane, 2000: Acclimation of ecosystem CO_2 exchange in the Alaska Arctic in response to decadal warming. *Nature,* **406,** 978-981.

Parmesan, C., and H. Galbraith, 2004: *Observed Impacts of Global Climate Change in the U.S*. Pew Center on Global Climate Change, Arlington, VA. Available at http://www.pewclimate.org/global-warming-in-depth/all_reports/observedimpacts

Parmesan, C., and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature,* **421,** 37-42.

Parmesan, C., 1996: Climate and species' range. *Nature,* **382,** 765-766.

Patz, J.A., M.A. McGeehin, S.M. Bernard, K.L. Ebi, P.R. Epstein, A. Grambsch, D.J. Gubler, P. Reiter, I. Romieu, J.B. Rose, J.M. Samet, and J. Trtanj, 2001: The potential health impacts of climate variability and change for the United States. Executive Summary of the report of the health sector of the U.S. National Assessment. *Journal of Environmental Health,* **64,** 20–28.

Peacock, W. G. (2003) 'Hurricane Mitigation Status and Factors Influencing Mitigation Status Among Florida's Single-Family Homeowners'. *Natural Hazards Review*. 4(3). pp. 1-10.

Pendleton, Linwood H. and Robert Mendelsohn, 1998: Estimating the Economic Impact of Climate Change on the Freshwater Sportsfisheries of the Northeastern U.S. *Land Economics* **74(4),** 483-96.

Peters, R.L., and T.E. Lovejoy, 1992: *Global Warming and Biological Diversity*. Yale University Press, New Haven, CT.

Pileus Project. Which factors are typically believe to have greatest inlufence on tourists; behavior. http://www.pileus.msu.edu/tourism/tourism_variables.htm

Pimentel, D., C. Wilson, C. McCullum, R. Huang, P. Dwen, J. Flack, Q. Tran, T. Saltman, and B. Cliff, 1997: Economic and environmental benefits of biodiversity. *Bioscience*, **47(11),** 747-757.

Ponting, C., 1991: *A Green History of the World: The Environment and the Collapse of Great Civilizations.* Penguin, New York, NY.

Porter, D. (ed.), 2000: *The Practice of Sustainable Development*. Urban Land Institute, Washington, DC.

Putnam, R., 2000: *Bowling Alone: The Collapse and Revival of American Community*. Simon and Schuster, New York, NY.

Putnam, R., 1995: Tuning in, tuning out: The strange disappearance of social capital in America, *Political Science and Politics*, **28(4)**, 664-683.

Putnam, R., 1993: *Making Democracy Work: Civic Traditions in Modern Italy*. Princeton University Press, Princeton, NJ.

Rahman, Tauhidur, 2007: Measuring the Well Being Across Countries. *Applied Economic Letters, 14 (11): 779-783.*

Raphael, D., R. Renwick, I. Brown, and I. Rootman, 1996: Quality of life and health: Current status and emerging conceptions. *Social Indicators Research*, **39,** 65-88.

Raphael, D., B. Steinmetz, R. Renwick, I. Rootman, I. Brown, H. Sehdev, S. Phillips, and T. Smith, 1999: The community quality of life project: A health promotion approach to understanding communities. *Health Promotion International*, **14(3),** 197-210.

Raphael, D., R. Renwick, I. Brown, B. Steinmetz, H. Sehdevc, and S. Phillips, 2001: Making the links between community structure and individual well-being: community quality of life in Riverdale, Toronto, Canada. *Health & Place,* **7,** 179-196.

Roback, Jennifer, 1988: Wages, rents, and amenities: Differences among workers and regions. *Economic Inquiry,* **26(1),** 23-41.

Roback, Jennifer, 1982: Wages, rents, and the quality of life. *Journal of Political Economy,* **90(6),** 1257-1279.

Root, T.L, J.T. Price, K.R. Hall, S.H. Schneider, C. Rozensweig, and J.A. Pounds, 2003: Fingerprints of global warming on wild animals and plants. *Nature*, **421,** 57-60.

Rose, A., K. Porter, N. Dash, J. Bouabid, C. Huyck, J.C. Whitehead, D. Shaw, R.T. Eguchi, C. Taylor, T.R. McLane, L.T. Tobin, P.T. Ganderton, D. Godschalk, A.S. Kiremidjian, and K. Tierney, and C.T. West, 2007. Benefit-cost analysis of FEMA hazard mitigation grants. *Natural Hazards Review,* **8(4)**, 97-111.

Rose, A., 2004: Defining and measuring economic resilience to disasters. *Disaster Prevention and Management,* **13,** 307-314.

Rosenberger, R. and J. Loomis, 2003: Benefit transfer. In: *A Primer on Non Market Valuation* [Champ, P., K. Boyle, and T. Brown (eds.)]. Kluwer Academic Publishers, Boston, MA, pp 445-482.

Ross, M.S., J.J. O'Brien, L. Da Silveira, and L. Sternberg, 1994: Sea-level rise and the reduction in pine forests in the Florida keys. *Ecological Applications,* **4,** 144-156.

Rothman, Dale S., Bas Amelung, and Philippe Poleme, 2003: *Estimating non-market impacts of climate change and climate policy*. Prepared for OECD Workshop on the Benefits of Climate Policy, Improving Information for Policy Makers. Available at www.oecd.org/dataoecd/6/30/2483779.pdf

Roy, D.B., and T.H. Sparks, 2000: Phenology of British butterflies and climate change. *Global Change Biology,* **6,** 407-416.

Sagarin, R.D., J.P. Barry, S.E. Gilman, and C.H. Baxter, 1999: Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs,* **69,** 465-490.

Saunders, S. and T. Easley, 2006: *Losing ground: Western National Parks endangered by climate disruption.* Rocky Mountain Climate Organization and Natural Resources Defense Council, New York, NY. Available at http://www.grandcanyontrust.org/whatsnew/documents/Globalwarmingparksreport08_14_06pdf.pdf

Scott, D., G. Wall, G. McBoyle, 2005: The evolution of the climate change issue tourism sector. In: *Tourism, Recreation and Climate Change* [Hall, C.M. and J. Higham (eds.)]. Channel View Publications, Buffalo, NY, pp. 44-62.

Scott, D. and B. Jones, 2005: *Climate Change and Banff National Park: Implications for Tourism and Recreation.* Faculty of Environmental Studies, University of Waterloo, Waterloo, Canada.

Scott, D., G. McBoyle and A. Minogue, 2006: Climate Change and the Sustainability of Ski-based Tourism in Eastern North America: A Reassessment. *Journal of Sustainable Tourism,* **14(4),** 376-398.

Scott, D., B. Jones, and J. Konopek. 2007. Implications of Climate and Environmental Change for Nature-Based Tourism in the Canadian Rocky Mountains. *Tourism Management 28(2): 570-579.*

Semenza, J.C., C.H.Rubin, and K.H. Falter, 1996: Heat-related deaths during the July 1995 heat wave in Chicago. *New England Journal of Medicine*, **335(2),** 84-90.

Shaw, D., 2005: *Water Resource Economics and Policy*. Edward Elgar Publishing, Northampton, MA.

Sillman, S. and P.J. Samson, 1995: Impact of temperature on oxidant photochemistry in urban, polluted, rural, and remote environments. *Journal of Geophysical Research,* **100,** 11497-11508.

Smit, B, and O. Pilifosova, 2001: Adaptation to climate change in the context of sustainable development and equity, chapter 18. In: *Climate Change 2001: Impacts, Adaptation, and Vulnerability – Contributions of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Smith, J.B., J.K. Lazo, and B. Hurd, 2003: The difficulties of estimating global non-market damages from climate change. In: *Global Climate Change: The Science, Economics, and Politics* [Griffin, J.M. (ed.)]. Edward Elgar, Northampton, Massachusetts.

Smith, V.K., 1983: The role of site and job characteristics in hedonic wage models. *Journal of Urban Economics*, **13(3),** 296-321.

Strzepek, Kenneth M., and Joel B. Smith (eds.), 1995: *As Climate Changes: International Impacts and Implications.* Cambridge University Press, Cambridge, New York, 340 pp.

Strzepek, K., D. Major, C. Rosenzweig, A. Iglesias, D. Yates, A. Holt, and D. Hillel, 1999: New methods of modeling water availability for agriculture under climate change: The U.S. corn belt. *Journal of the American Water Resources Association,* **35(6),** 1639-1656.

Sufian, A.J.M., 1993: A multivariate analysis of the determinants of urban quality of life in the world's largest metropolitan areas. *Urban Studies*, **30(8),** 1319-1329.

Tainter, J., 1998: *The Collapse of Complex Societies*. Cambridge University Press, Cambridge, England.

Tierney, K., 1997: Impacts of recent disasters on businesses: The 1991 Midwest floods and the 1994 Northridge earthquake. In: *Economic Consequences of Earthquakes: Preparing for the Unexpected* [B. Jones (ed.)]. National Center for Earthquake Engineering Research, Buffalo, NY.

Tol, R.S.J., 2005: The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties. *Energy Policy*, **33(16),** 2064-2074.

Tol, R.S.J., 2002: Welfare specifications and optimal control of climate change: an application of fund. *Energy Economics,* **24,** 367-376.

Toman, M.A. 1998: Why not calculate the value of the world's ecosystem services and natural capital? *Ecological Economics* **25**, 57-60.

U.S. EPA, 2000: *Guidelines for Preparing Economic Analyses*. EPA 240-R-00-003, Washington, DC.

U.S. EPA, 1997: *The Benefits and Costs of the Clean Air Act, 1970-1990.* Report to Congress, Washington DC.

U.S. EPA. 1995. *Ecological Impacts from Climate Change: An Economic Analysis of Freshwater Recreational Fishing.* EPA 220-R-95-004. Washington DC.

U.S. EPA, 1989: *The Potential Effects of Global Climate Change on the United States*. J.B. Smith and D.A.Tirpak (eds.). EPA-230-05-89-050, Washington, DC.

Vaughan, W.J. and C.S. Russell. 1982. *Freshwater Recreational Fishing: The National Benefits of Water Pollution Control*. Resources for the Future, Washington DC.

Vedlitz, A, Letitia T. Alston, Shirley B. Laska, Robert B. Gramling, Mark A. Harwell and Helen D. Worthen, 2007. *Use of Science in Gulf of Mexico Decision Making Involving Climate Change.* Project Final Report. Prepared for the U.S. Environmental Protection Agency under Cooperative Agreement No. R-83023601-0. December.

Veenhoven, R., 1988: The utility of happiness. *Social Indicators Research*, **20,** 333-354.

Veenhoven, R., 1996: Happy life-expectancy, A comprehensive measure of quality of life in nations. *Social Indicators Research,* **39,** 1-58.

Veenhoven, R., 2000: The four qualities of life. *Journal of Happiness Studies*, **1,** 1-39.

VEMAP Members, 1995: Vegetation/ecosystem modeling and analysis project: Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochemical Cycles,* **9,** 407-437.

Viscusi, W. Kip and Joseph Aldy, 2007: Labor Market Estimates of the Senior Discount for the Value of Statistical Life. *Journal of Environmental Economics and Management*, **53**, 377-392.

Viscusi, W. Kip, 1993: The value of risks to life and death. *Journal of Economic Literature,* **31(4),** 1912-1946.

Wall, G., 1998: Implications of global climate change for tourism and recreation in wetland areas. *Climate Change,* **40,** 371-389.

Wang, G., N.T. Hobbes, H. Galbraith, D.S. Ojima, K.M. Giesen, 2002: Signatures of large-scale and local climates on the demography of white-tailed ptarmigan in Rocky Mountain National Park, Colorado, USA. *International Journal of Biometeorology,* **46,** 197-201.

Warren, Rachel, Chris Hope, Michael Mastrandrea, Richard Tol, Neil Adger, and Irene Lorenzoni, 2006: *Spotlighting impacts functions in integrated assessment.* Research report prepared for the Stern review on the economics of climate change. Available at http://www.tyndall.ac.uk/publications/working_papers/twp91.pdf

Warren, R.S., and W.A. Niering, 1993: Vegetation change on a northeast tidal marsh: interaction of sea-level rise and marsh accretion. *Ecology,* **74,** 96–103.

Weniger, B.G., M.J. Blaser, J. Gedrose, E.C. Lippy, and D.D. Juranek, 1983: An outbreak of waterborne giardiasis associated with heavy water runoff due to warm weather and volcanic ashfall. *American Journal of Public Health,* **73(8),** 868-872.

Woodward, R.T. and Y.S. Wui, 2001: The economic value of wetland services: A meta-analysis. *Ecological Economics,* **37,** 257-270.

World Health Organization (WHO), 1997: *City Planning for health and sustainable development*. WHO Regional Office for Europe, Copenhagen. Available at: http://www.euro.who.int/document/wa38097ci.pdf

Yohe, G., J. Neumann, and P. Marshall, 1999: The economic damage induced by sea level rise in the United States. In: *The Impact of Climate Change on the United States Economy*. [Mendelsohn, R. and J. Neumann (eds).]. Cambridge University Press, Cambridge, UK, pp. 178-208.

Zahran, S., S. Brody, A. Vedlitz, H. Grover, and C. Miller, 2008. Vulnerability and capacity: Explaining local commitment to climate change policy. *Environment and Planning C: Government and Policy* advance online publication, doi:10.1068/c2g [published online 5 March 2008].

4.7 Appendix 1:

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

Assessments of the benefits and costs, whether explicit or tacit, underlie 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, 2004). 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, 2004). 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

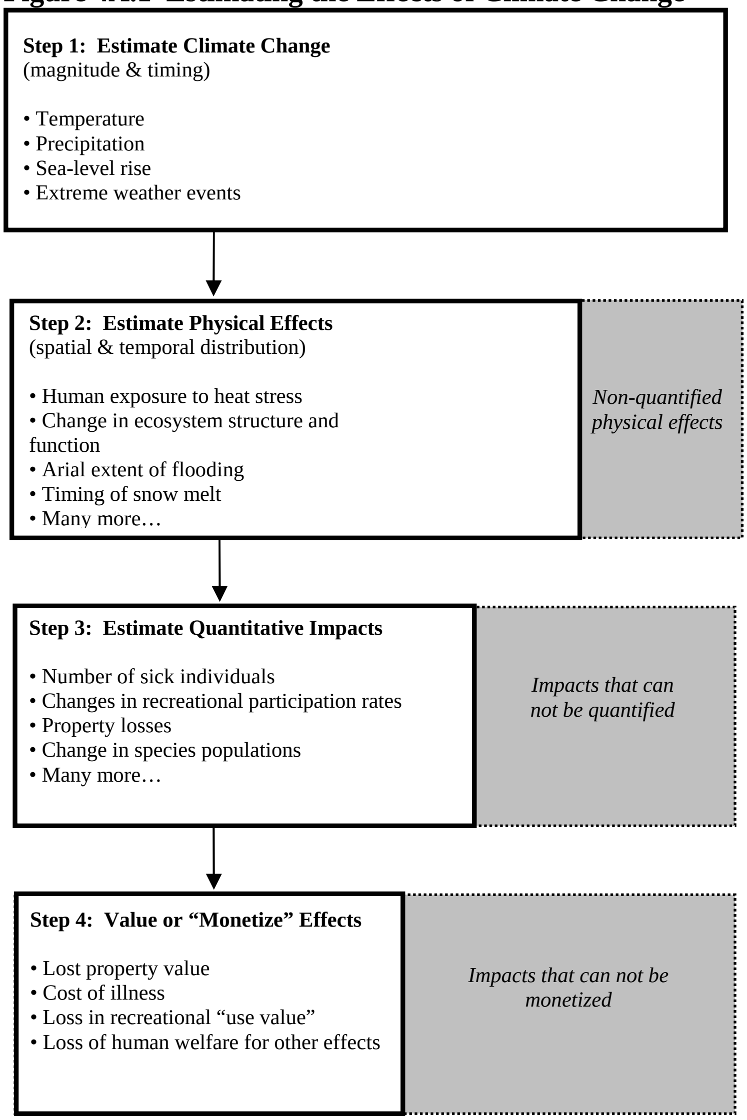
The process of estimating the effects of climate change, including effects on human welfare, involves up to four steps, illustrated in Figure 4A.1. Moving down from the top of Figure 4A.1, the gray area occupies a larger portion of each box, indicating (in rough terms) that at each stage it is more and more difficult to develop quantified, rather than qualitative, results.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 out 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 4A.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.[34] 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.

[34] 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 might 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.

By 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, are a provider of health insurance, 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.

4.8 Boxes

Box 4.1 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; Root *et al.*, 2003; 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°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 have 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.

Box 4.2 Case Study of the Effects of Climate Change on Rocky Mountain 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 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.

Loomis and Richardson (2006) compared two approaches to estimating the effect of climate change on visitation and employment in RMNP. The first approach examined 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°F) by 7.5%.

The second approach used a survey that portrayed the direct effects (e.g., temperature) and indirect effects (e.g., changes in elk and ptarmigan (an alpine bird), or percent of the park in tundra). Visitors were then asked to indicate if they would change their visits to RMNP or length of stay in the park. The surveys used three climate change scenarios, one produced by the Canadian Climate Center (CCC) indicating a 4°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°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 4.6 shows the results of the CCC, Hadley, and Extreme Heat temperature scenarios on visitation, visitor benefits and tourism employment as compared to current conditions. As indicated in the table, applying visitor survey estimates of visitation change yields a 13.6% increase with CCC and 9.9% increase with Hadley. Loomis and Richardson also report that applying the historic visitation patterns to the same scenarios yields an 11.6% increase in visitation with CCC and 6.8% 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. In the extreme heat scenario, however, visitations declines from current conditions.

4.9 Tables

Table 4.1 Categorization of Well-Being

Category of Well-being	Description and Rationale	Components / Indicators of Well-being	Illustrative Metrics / Measures of Well-being	Examples of Negative 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.	▪ Income and production ▪ 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 ▪ Equity in the distribution of income	▪ Gross Domestic Product (GDP) ▪ 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 rates ▪ 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.

Table 4.2 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-based jobs (including recreation) fall as resources decline	Economic conditions	Number of jobs, unemployment 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

Table 4.3 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.

Table 4.4 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)		

Table 4.5 Comparison of Changes in US Visitor Days

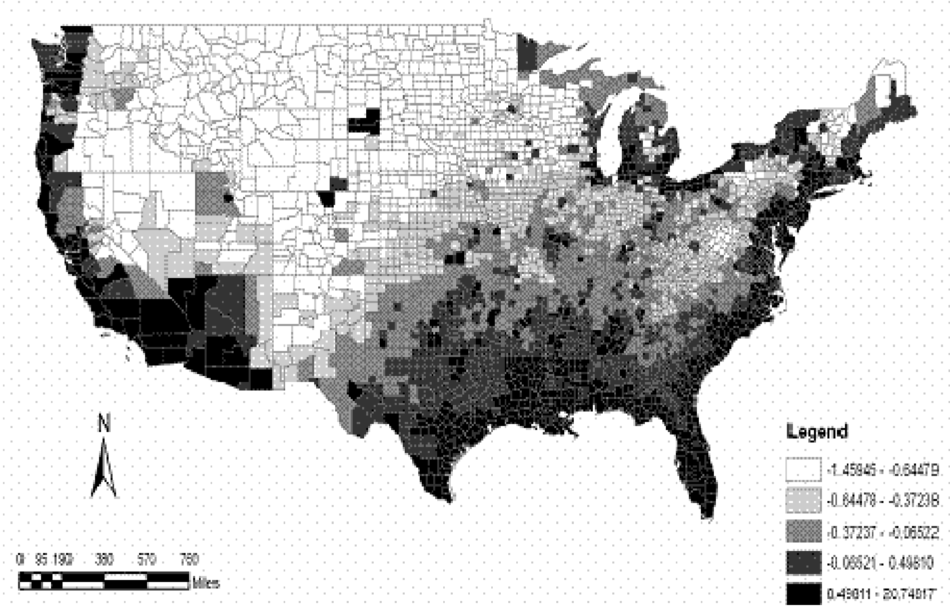
Activity	Loomis and Crespi (1999)	Mendelsohn and Markowski (1999)
Boating	9.2%	36.1%
Camping	-2.0%	-12.7%
Fishing	3.5%	39.0%
Golf	13.6%	4.0%
Hunting	-1.2%	no change
Snow Skiing	-52.0%	-39.0%
Wildlife Viewing	-0.1%	-38.4%
Beach Recreation	14.1%	not estimated
Stream Recreation	3.4%	included in boating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

Table 4.6 Change in Visits, Jobs and Visitor Benefits with Three Climate Change Scenarios

Climate Scenario	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

4.10 Figures

Figure 4.1 Geography of Climate Change Vulnerability at the County Scale



Three measures of climate change risk are used to create the vulnerability index: expected temperature change, extreme weather event history, and coastal proximity. Risk measures are geo-referenced at the county scale. The expected *temperature change* variable is measured as the expected unit change in average minimum temperature (in degrees Celsius) for a county from 2004 to 2099. Temperature data are from the Hadley Center. Hadley Center monthly time series data on average minimum temperature for the United States are plotted at the 0.5 x 0.5 degree of spatial resolution. In cases where climate cells intersect county boundaries, temperature data are averaged across intersecting climate cells. To estimate extreme weather event history we summarize the number of reported injuries and fatalities from hydro-meterological hazard events at the county level from Jan 01, 1960 to Jul 31, 2004. Higher values on our natural hazard casualty variable reflect more pronounced histories of injury and death from extreme weather events. Casualty data were collected from the Spatial Hazard Events and Losses Database for the United States (SHELDUS). The *coastal proximity* variable is measured dichotomously. A county receives a score of 1 if it is designated by the National Oceanic and Atmospheric Administration (NOAA) as an "at-risk coastal" county, and a score of 0 if it is not. NOAA defines a county as at-risk coastal if at least 15 percent of its total area is located in a coastal watershed. The vulnerability index was created by standardizing then summing each measure of climate change risk (z-score). The distribution of vulnerability is divided into equal quintiles, with darker colors reflecting higher vulnerability to climate change.

Figure 4.2 Steps from Climate Change to Economic Valuation of Ecosystem Services

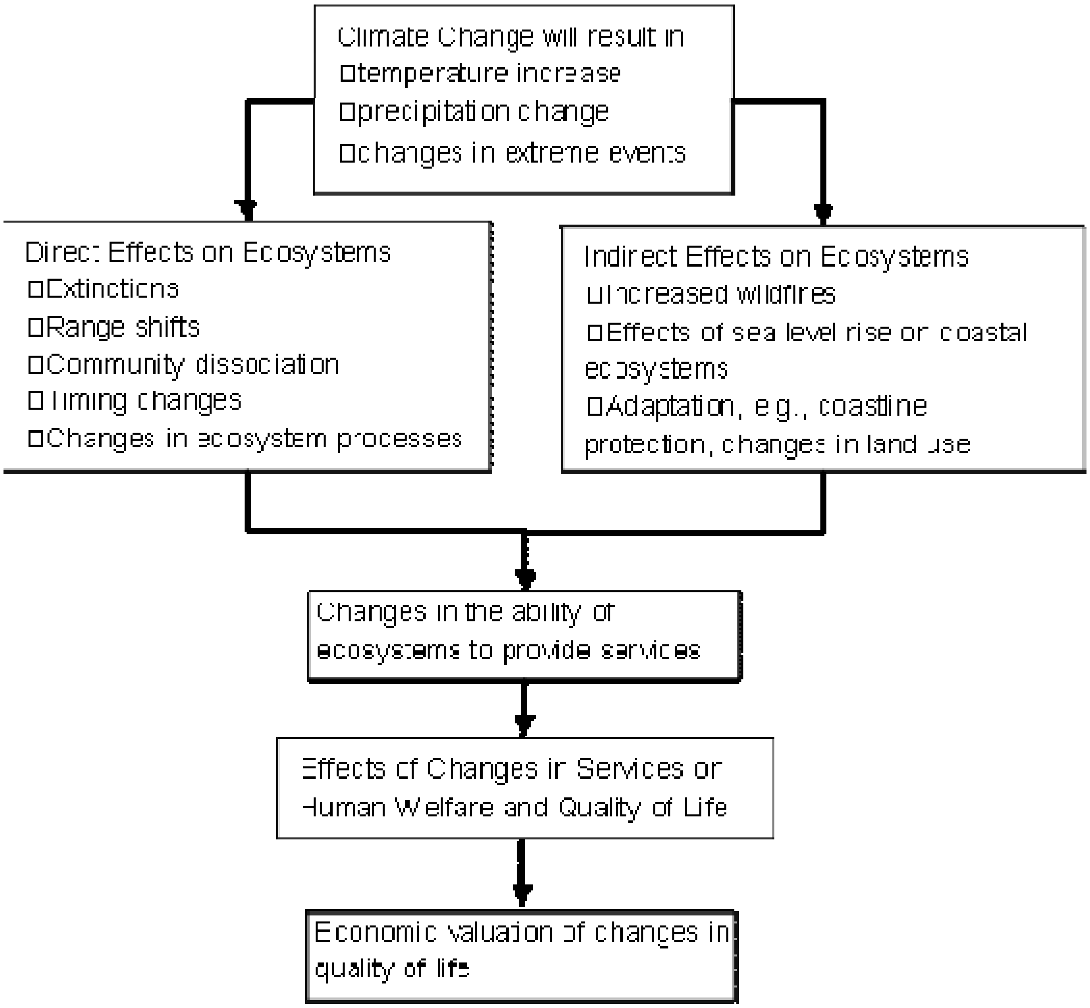
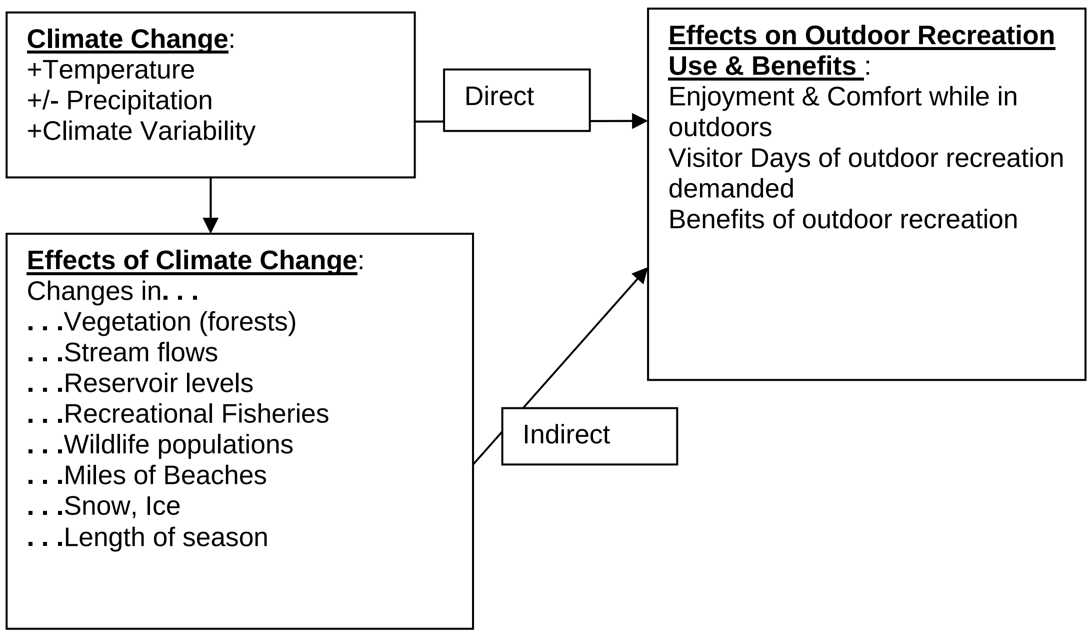


Figure 4.3 Direct and Indirect Effects of Climate Change on Recreation



Synthesis and Assessment Product 4.6

Chapter 5

Common Themes and Research Recommendations

Convening Lead Author: Janet L. Gamble, U.S. Environmental Protection Agency

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

Contributing Authors: Colleen E. Reid, ASPH Fellow, John V. Thomas, U.S. Environmental Protection Agency, Christopher P. Weaver, U.S. Environmental Protection Agency

Table of Contents

5.1 Synthesis and Assessment Product 4.6: Advances in the Science

The Synthesis and Assessment Product 4.6 assesses the impacts of climate variability and change on human systems in the United States. Each of the assessment chapters have drawn on different literatures, with generally more available scientific knowledge on impacts and adaptations related to human health, somewhat less related to human settlements, and still somewhat less related to human welfare.

Several themes recur across these chapters and point to advances in the science of climate impacts assessment and the development and deployment of adaptation responses.

- Climate change is connected to other environmental and social changes in a complex and dynamic fashion. In some cases climate change compounds other global changes, while in other cases the impacts of climate change are determined or moderated by other socioeconomic factors (5.1.1).
- Extreme weather events will play a defining role, particularly in the near term, shaping climate-related impacts and adaptive capacity. While impacts associated with changes in climate averages may be less important now, these averages are expected to have more pronounced long-run effects on sea level rise, permafrost melt, glacial retreat, drought patterns and water supplies, etc. (5.1.2).
- Climate change will have a disproportionate impact on disadvantaged groups in communities across the U.S. Some regions and some resources are more vulnerable to climate impacts, such as coastal zones, drought-prone regions, and flood-prone river basins (5.1.3).
- Adaptation of infrastructure and services to climate change may be costly, but many communities will have adequate resources. However, for places already struggling to provide or maintain basic public amenities and services, the additional costs of adaptation will impose a potentially-insupportable burden (5.1.4.).
- With such a complex scientific and policy landscape, an integrated multi-disciplinary framework is needed to enable climate change impacts to be measured in meaningful ways and for optimal mitigation and adaptation strategies to be identified, developed, and deployed (5.1.5).

5.1.1 Complex Linkages and a Cascading Chain of Impacts Across Global Changes

Climate is only one of a number of global changes that impact human well-being. The major effects of climate will be shaped by interactions with non-climate stressors. As such, climate change will seldom be the sole or primary factor determining a population's or a location's well-being. The impacts of climate variability and change interact with impacts tied to population growth and change and other socioeconomic endpoints (for example, impacts on infrastructure capacity, water supplies, habitat preservation, community growth and development, and access to health care). While this assessment focuses on how climate change could affect the future health, well-being, and settlements in the U.S., the extent of any impacts will depend on an array of non-climate factors, including:

- demographic changes related to the location, size, age and characteristics of populations;

- population and regional vulnerabilities;
- future social, economic, and cultural contexts;
- availability of natural resources;
- human, cultural and social capital;
- advances in science and technology;
- characteristics of the built environment;
- land use change; and
- public health and public utility infrastructures; and
- the capacity and availability of health and social services.

The effects of climate change very often spread from directly impacted areas and sectors to other areas and sectors through extensive and complex linkages. The importance of climate change depends on the directness of the climate impact coupled with 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 lost, but also on the devastating impacts on infrastructure, neighborhoods, businesses, schools, and hospitals as well as in the personal disruption of family and friends in established communities, with lost lives and lost livelihoods, challenged 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 capacity of extreme weather events.

5.1.2 Changes in Climate Extremes and Climate Averages.

Climate variability and change are important stressors. Their potential impacts on health, settlements, and welfare result in two broad categories of effects:

- changes in extreme weather events (e.g., hurricanes, heat waves and urban heat island effects, etc.) and
- changes in average climate conditions (e.g., reduced snowfalls, earlier snowmelt, hotter summer average temperatures, drought conditions, etc.).

Some changes in the average climate conditions have strong potential to impact human systems. For example, changes in the growing season or the timing and amount of spring runoff. Higher minimum temperatures are related to the spread of ticks as well as the increase in deaths associated with heat waves. The effects of other climate changes, such as the perceived relationship between people and their environment (e.g., aesthetics, recreational opportunities, etc.), have not yet been well studied. Key vulnerabilities are often defined by climate phenomena that exceed thresholds for adaptation. Their severity is not only related to the rate and magnitude of climate change, particularly extreme weather events and/or abrupt climate change, but also by limited access to resources for coping across a range of social systems. In many parts of the U.S. and across many segments of the population, livelihoods and lifestyles are likely to be affected by climate change. Net valuations of benefits vs. costs from climate effects will vary, but they are more likely to be strongly negative if climate change is substantial and rapid in onset rather than moderate and gradual.

Thresholds in human systems, below which effects are relatively minor, but above which the joint pressure of all the minor effects overwhelms the capacity to cope, are poorly understood. Focused research on thresholds would substantially improve understanding of climate impacts. Depending on the degree and speed of climate change and on the effectiveness of adaptation strategies, adverse human welfare outcomes may increase even as total burdens of climate-sensitive outcomes decrease given infrastructure and technology improvements.

5.1.3 Vulnerable Populations and Vulnerable Locations

Impacts of climate variability and change on human systems are location- and population-specific. For instance, in densely-developed coastlines, populations are especially vulnerable to tropical storms, storm surge and flooding, just as the very old and the very young residing in urban areas experience increases in cardiovascular and pulmonary morbidity and mortality caused by extreme heat coupled with degraded air quality. Native American peoples in Alaska and other low socio-economic communities because of their decreased economic capacity to prepare for and respond to the impacts of climate change. Just as there are differences across populations, there are important differences in vulnerability across geographic regions, such as the exposure to extreme events along the Gulf Coast and water supply issues in the southeast, the southwest and the Inter-Mountain West.

With respect to health impacts from climate variability and change, specific subpopulations may experience heightened vulnerability for climate-related health effects associated with:

1. **Biological sensitivity** related to age (especially the very young and the very old), the presence of pre-existing chronic medical conditions (such as the sensitivity of people with chronic heart and pulmonary conditions to heat-related illness), developmental characteristics, acquired factors (such as immunity), those taking certain medications (e.g. some antihypertensive and psychotropic medications) and genetic factors (such as metabolic enzyme subtypes that play a role in vulnerability to air pollution effects).

2. **Socioeconomic factors** also play a critical role in determining vulnerability to environmentally-mediated factors. The distribution of climate-related effects will vary among those who live alone; those with limited rights (for instance, some in the immigrant communities); by economic strata; by housing type and according to other elements that either accentuate or limit vulnerability. Socioeconomic factors may increase the likelihood of exposure to harmful agents, interact with biological factors that mediate risk (such as nutritional status), and/or lead to differences in the ability to adapt or respond to exposures or to early phases of illness and injury.

3. Given their **location**, the underlying vulnerability of some communities is inherently high just as their adaptive capacity is similarly limited. Populations in gently-sloping coastal areas are particularly vulnerable to sea level rise and settlements along floodplains of large rivers are particularly vulnerable due to projections of increased variability in precipitation. Projections of increased frequencies of drought combined put the increasing populations of desert southwest cities at risk.

It is essential that public health interventions and preventions recognize populations that may experience interactive or synergistic effects of multiple risk factors for health problems, both related to climate change and to other global changes. Poor communities and households are already under stress from climate variability and climate-related extreme events such as heat waves, hurricanes, and tropical and riverine flooding. Since they tend to be concentrated in relatively high-risk areas, have limited access to services and other resources for coping, they can be especially vulnerable to climate change. These differential effects propagate concerns regarding social inequity and environmental justice and increased pressure for adaptive responses from local, state, and federal governments.

5.1.4. The Cost of and Capacity for Adaptation

U.S. society is capable of considerable adaptation, depending heavily on the competence and capacity of individuals, communities, federal, state, and local governments, and available financial and other social resources. While adaptation to climate change will come at a cost that may reduce available resources to cope with other societal burdens, potentials for adaptation through technological and institutional development and behavioral changes are considerable, especially where such developments meet other sustainable development needs.

With scarce resources, communities should also choose adaptation options with co-benefits that help ameliorate other issues or where they can easily add climate concerns to existing response plans. The focus on all-hazards response within public health agencies can simply add climate impacts to its list of hazards for which to prepare. This will likely improve their response plans to events in the near term such as storms that happen in a variable climate, whether or not they increase in frequency or intensity with a changing climate. Planting trees and green roofs to reduce urban heat islands has the added benefit of creating a more aesthetically pleasing location that increasing well-being and by decreasing energy use in these buildings. Thus, some adaptation measures can also considered mitigation measures.

Resiliency – a central concept in assessing the vulnerability and adaptability of regions, communities, and individuals – will depend on both physical and social infrastructure. Social infrastructure includes factors such as human capital (e.g. formal education), cultural capital (e.g. breadth of linguistic mastery), economic capital, and social capital (e.g. ties within social networks). Each of these assets vary from community to community and from individual to individual. Collectively, non-economic capital provides both assets and buffers for communities and individuals.

5.1.5 An Integrative Framework

The impacts of climate variability and change on human health and human settlements are fairly well characterized, though additional research is needed to refine impact assessments and provide better decision support (particularly with respect to deploying adaptation measures). Human welfare is an emerging concept, similar in purpose to something like “sustainability.” As an organizing principal, human welfare integrates multiple impacts across diverse sectors and regions into an internally-consistent, coherent framework for assessing costs, benefits, and tradeoffs.

Sustainable development offers an alternative to traditional urban / suburban settlement patterns. The focus on sustainability has evolved as an effort to curb individual consumption and to minimize the collective footprint of communities on natural resources, ecosystems, pollution, and anthropogenic emissions of greenhouse gases that contribute to 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 resilience within 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 resources, and social systems. Resiliency, a central concept in measuring the vulnerability and adaptability of communities and individuals depends not only on physical infrastructure, but also on social infrastructure. Social infrastructure includes factors such as human capital (e.g. formal education), cultural capital (e.g. extent of linguistic mastery), and social capital (e.g. ties to social networks). Each of these assets varies from community to community and from individual to individual. These non-economic capital goods provide both assets and buffers for communities and individuals.

Related to sustainable development is the concept of smart growth which has been described as an alternative to sprawl, traffic congestion, disconnected neighborhoods and inner city decay. It explicitly considers long-term costs and consequences of growth, 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. Some communities of the 21st Century are 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 these communities and enhance their overall resilience.

The potential for utilizing human welfare as an integrating framework is not yet mature, and additional research will be needed, including, for example, deriving valuation methodologies. As an integrating concept, human welfare can provide insight into the determinants of human happiness. Just as health is an indicator of welfare, especially as physical health is closely tied to individual measures of happiness, contentment, and well-being, similarly determinants of well-being are derived from aspects of human settlements. Collectively, human welfare is a measure of what makes people, their families, and their communities satisfied.

5.2 Expanding the Knowledge Base

The present state of the science suggests that opportunities remain for addressing critical research areas. The SAP 4.6 concludes that climate observations and modeling are becoming increasingly important for a wide segment of public and private sector entities, such as water resource managers, public health officials, agribusinesses, energy providers, forest managers, insurance companies, and urban and transportation planners. In order to more accurately portray the consequences of climate change and support better-informed adaptation strategies, research efforts should focus on:

- deriving socioeconomic scenarios that describe how the world may evolve in the future, including assumptions about changes in societal characteristics, governments and public policy, as well as economic and technological development.

- connecting those socioeconomic scenarios with downscaled climate models to create projections of future changes in climate, including the intensity and severity of extreme weather events, at the regional and local scales.
- characterizing the costs of climate change, both those that relate to impacts and those that relate to response strategies (including adaptation and mitigation).
- estimating the damages avoided by stabilizing or reducing emissions.
- determining the factors that contribute to synergies between adaptive capacity and sustainable development as well as synergies between adaptation and mitigation.
- pursuing cross-disciplinary efforts that focus on the human dimensions of climate change in an integrated fashion.
- improving capacity to incorporate scientific knowledge about climate, including uncertainty, in existing adaptation strategies.
- conducting research at regional and sectoral levels that promote analyses of the response of human and natural systems to multiple stresses. Impacts of climate change are most damaging when they occur in a context of multiple climate and non-climate stressors.
- evaluating the adaptation strategies that effectively address challenges presented by current non-climate stressors (e.g., land use and population dynamics) as well as anticipated climate change impacts and develop comprehensive estimates of these co-benefits.
- implementing adaptation measures to address the near- and long-term responses to climate change, using regional and local stakeholders as key stakeholders in the development of effective, responsive, and timely adaptation policies.
- advancing the concept of human welfare as an integrating framework by developing methods to achieve comparable and comprehensive valuations across diverse impacts and sectors.
- determining which climate impacts exhibit thresholds. Threshold-based damage functions can be fundamentally different in their nature and extent than continuous damage functions.
- supporting research on impacts and the development, implementation and evaluation of adaptive responses by collecting high quality time-series measurements and other observations of both climate and human systems.
- identifying early effects of changing weather patterns on climate-sensitive outcomes

The SAP 4.6 concludes that assessments should be periodically conducted to re-examine the rapidly emerging knowledge base in this area. Gaps should be addressed that characterize exposure and sensitivity at the local or regional level. Research should evaluate the adaptive capacity of places and institutions to climate-induced risks. Key research and development areas should address short-term risk assessment and evaluation of the costs and effectiveness of near-term adaptive strategies as well as longer-term impacts and responses.

The following sections provide a more detailed discussion of research needs and recommendations by topic: human health, human settlements, and human welfare. There is significant overlap across topics with opportunities for investigating cross-disciplinary pursuits of research opportunities and adaptation responses.

5.2.1 Human Health Research Gaps

An important shift in perspective has occurred since the Health Sector Assessment of the First National Assessment in 2001. There is a greater appreciation of the complex pathways by which weather and climate affect individual and societal health and well-being. In the research community, there is a more finely-honed understanding of the interaction of multiple non-climate, social, and behavioral factors and impacts on risks from injury and disease. While significant gaps remain, several gaps identified in the First National Assessment have been addressed, including:

- a more finely honed understanding of the differential effects of temperature extremes by community, demographic, and biological characteristics;
- improved characterization of the exposure-response relationships to extreme heat; and
- improved understanding of the public health burden posed by climate-related changes from heat waves and air pollution.

Despite these advances, the body of literature has only limited quantitative projections of future impacts. More research is needed to ensure the U.S. public health and medical care systems and at-risk populations are adequately prepared to cope with projected changes in climate. The following specific suggestions for research on climate change and human health:

- Increase the skill with which we characterize exposure-response relationships, including identifying thresholds and particularly vulnerable groups, considering relevant factors that affect the geographic range and incidence of climate-sensitive health outcomes, and including disease ecology and transmission dynamics.
- Develop quantitative models of possible health impacts of climate change that can be used to explore a range of socioeconomic and climate scenarios.
- Evaluate effectiveness of current adaptation projects, including the costs and benefits of interventions. For example, heat wave and health early warning systems have not been effective; further research is needed to understand how public health messages can be made more helpful.
- Characterize with local stakeholders the local and regional scale vulnerability and adaptive capacity related to the potential risks and the time horizon over which climate risks might arise.
- Anticipate requirements for infrastructure such as may be needed 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.

5.2.2 Human Settlements Research Gaps

Chapter 3 examines the vulnerabilities and impacts of climate change and variability on human settlements. The following list enumerates many research topics that would help expand the knowledge base of the linkages between climate change and human settlements.

- Advance the understanding of settlement vulnerabilities, impacts, and adaptive responses in a variety of different local contexts around the country.
- Develop plans for out-migration from vulnerable locations via realistic, socially acceptable strategies for shifting human populations away from vulnerable zones.

- Improve the understanding of vulnerable populations (such as the urban poor and native populations on rural, tribal lands) that have limited capacities for response to climate change in order to provide a basis for adaptation research that addresses social justice and environmental equity concerns.
- Improve the understanding of how urban decision-making is changing as populations become more heterogeneous and decisions become more decentralized especially as this affects adaptive responses.
- Improve 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. With continued growth in 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.
- Improve the understanding of relationships between settlement patterns (both regional and intra-urban) and resilience/adaptation.
- Improve the understanding of vulnerabilities of urban population inflows and outflows to climate change impacts.
- Improve the understanding of second and third-order impacts of climate change in urban environments, including interactive effects among different aspects of the urban system.
- Review 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 well-developed partnerships across local, state, and federal governments, industry, non-governmental organizations, foundations, stakeholders, resource managers, urban planners, public utility and public health authorities, and the academic research community.

5.2.3 Human Welfare Research Gaps

Despite the potential for impacts on human well-being, little research focuses directly on understanding the relationship between well-being and climate change. Completely cataloging the effects of global change on human well-being or welfare would be an immense undertaking, and no well-accepted structure for doing so has been developed and applied. 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 may include changes that are not easily captured by objective measures of well-being or quality of life.

Developing an understanding of the impacts of climate change on human welfare will require steps designed to develop a framework for addressing individual and community welfare and well-being, as well as to fill the data gaps associated with the estimation and quantification of effects. Some specific steps that will help expand the knowledge base related to climate change and human welfare are listed below.

- Determine an appropriate definition of human welfare/well-being for climate analysis.

- Design an appropriate method for systematically categorizing and identifying impacts on welfare/well-being.
- Identify priority categories for data collection and research in order to establish and quantify the linkage from climate to effects on welfare/well-being.
- Decide which metrics should be used for these categories; more generally, which components of welfare/well-being should be measured in natural or physical units, and which should be monetized.
- Investigate methods by which diverse metrics can be aggregated, or at least weighted and compared in policy decisions where aggregation is impossible.
- Develop an approach for addressing those human welfare effects that are difficult to look at in a piecemeal way, such as welfare changes on communities or ecosystem services.
- Identify appropriate top-down and bottom-up approaches for estimating impacts and value (whether economic or otherwise) of the most critical categories of welfare/well-being.

Together, these steps should enable researchers to make progress towards promoting the consistency and coordination in analyses of welfare/well-being that will facilitate developing the body of research necessary to analyze impacts on human welfare, well-being, and quality of life.

Synthesis and Assessment Product 4.6
Appendix 1. Glossary

Sources: Derived from the Intergovernmental Panel on Climate Change Third and Fourth Assessment Reports, Working Group II and other sources as indicated.

Words in italics indicate that the following term is also contained in this glossary.

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.

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

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.

Algal bloom

[1] *The American Heritage® Dictionary of the English Language, Fourth Edition*. Retrieved November 21, 2007, from Dictionary.com website: http://dictionary.reference.com/browse/aeroallergen

A reproductive explosion of algae in a lake, river or ocean.

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.

Aquifer
A stratum of permeable rock that bears water. An unconfined aquifer is recharged directly by local rainfall, rivers and lakes, and the rate of recharge will be influenced by the permeability of the overlying rocks and soils.

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.

Biofuel
A fuel produced from organic matter or bombustible oils produced by plants. Examples of biofuel include alcohol, black liquor from the paper-manufacturing process, wood, and soybean oil.

Biogenic[2]
Produced by living organisms or biological processes.

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 industrial processes. It is the principal *anthropogenic greenhouse gas* that affects

[2] *The American Heritage® Dictionary of the English Language, Fourth Edition*. Retrieved November 21, 2007, from Dictionary.com website: http://dictionary.reference.com/browse/biogenic

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.

Chronic obstructed pulmonary disease (COPD)[3]

Chronic obstructive pulmonary disease, or COPD, refers to a group of diseases that cause airflow blockage and breathing-related problems. It includes emphysema, chronic bronchitis, and in some cases asthma.

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 any change in *climate* over time, whether due to natural variability or as a result of human activity. This usage differs from that in the *United Nations Framework Convention on Climate Change (UNFCCC)*, which 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'. See also *climate variability*.

Climate change commitment

Due to the thermal inertia of the ocean and slow processes in the *biosphere*, the *cryosphere* and land surfaces, the climate would continue to change even if the atmospherica composition was held fixed at today's values. Past changes in atmospheric position leads to a 'committed' *climatic change* which continues for as long as a radiative imbalance persists and until all components of the *climate system* have adjusted to a new state. The further change in temperature after the composition of the *atmosphere* is head constant is referred to as the committed warming or warming commitment. Climate change commitment includes other future changes, for example in the hydrological cycle, in *extreme weather events*, and in *sea-level rise.*

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,

[3] Definition taken from http://www.cdc.gov/nceh/airpollution/copd/copdfaq.htm visited on November 21, 2007.

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*.

Communicable Disease

An *infectious disease* caused by transmission of an infective biological agent (virus, bacterium, protozoan, or multicellular macroparasite).

Confidence

In this Report, the level of confidence in a statement is expressed using a standard terminology defined in the Introduction. See also *uncertainty*.

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

DALY (Disability-adjusted life years)[4]

The sum of years of life lost due to premature death and illness, taking into account the age of death compared with natural life expectancy and the number of years of life lived with a disability. The measure of number of years lived with the disability considers the duration of the disease, weighted by a measure of the severity of the disease.

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**.**

Dose-response function[5]

A mathematical relationship is established which relates how much a certain amount of exposure impacts on production, capital, ecosystems, human health etc.

Downscaling

A method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses.

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.

[4] Definition from the glossary of the Millenium Ecosystem Assessment, 2005.

[5] Definition modified from http://stats.oecd.org/glossary/detail.asp?ID=6404 visited on November 21, 2007.

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 processes
The processes that underpin the integrity and functioning of ecosystems, such as decomposition, carbon cycling, or soil renewal, etc.

Ecosystem services
Ecological processes or functions that have monetary or non-monetary *value* to individuals or society. There are (i) supporting services such as productivity or *biodiversity* maintenance, (ii) provisioning services such as food, fibre, or fish, (iii) regulating services such as climate regulation or *carbon sequestration*, and (iv) cultural services such as tourism or spiritual and aesthetic appreciation.

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).

F

Food security
A situation that exists when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development and an active and healthy life. Food insecurity may be caused by the unavailability of food, insufficient purchasing power, inappropriate distribution, or inadequate use of food at the household level.

Foodborne illness[6]
An illness caused by consuming foods or beverages contaminated with any of many different disease-causing microbes, or pathogens, or poisonous chemicals, or other harmful substances.

Footprint (ecological)[7]
An index of the area of productive land and aquatic ecosystems required to produce the resources used and to assimilate the wastes produced by a defined population at a specified material standard of living, wherever on Earth that land may be located.

Forecast
See *climate prediction* and *climate projection*.

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*.

GIS (Geographic Information Systems)[8]
A computerized system organizing data sets through a geographical referencing of all data included in its collections.

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

[6] Definition modified from the Centers for Disease Control and Prevention website: http://www.cdc.gov/ncidod/dbmd/diseaseinfo/foodborneinfections_g.htm, viewed on November 21, 2007.
[7] From the glossary of the Millenium Ecosystem Assessment, 2005.
[8] From the glossary of the Millenium Ecosystem Assessment, 2005.

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.

Globalization

The growing integration and interdependence of countries worldwide through the increasing volume and variety of crossborder transactions in goods and services, free international capital flows, and the more rapid and widespread diffusion of technology, information and culture.

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).

Gross Domestic Product

Gross Domestic Product (GDP) is the monetary value of all goods and services produced within a nation.

Gross National Product

Gross National Product (GNP) is the monetary value of all goods and services produced in a nation's economy, including income generated abroad by domestic residents, but without income generated by foreigners.

Groundwater Recharge

The process by which external water is added to the zone of saturation of an *aquifer*, either directly into a formation or indirectly by way of another formation.

H

Habitat

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

Hantavirus

A virus in the family *Bunyaviridae* that causes a type of haemorrhagic fever. It is thought that humans catch the disease mainly from infected rodents, either through direct contact with the animals or by inhaling or ingesting dust that contains aerosolized viral particles from their dried urine and other secretions.

Healthy Cities Program[9]

The WHO Healthy Cities programme engages local governments in health development through a process of political commitment, institutional change, capacity building, partnership-based planning and innovative projects. It promotes comprehensive and systematic policy and planning with a special emphasis on health inequalities and urban poverty, the needs of vulnerable groups, participatory governance and the social, economic and environmental determinants of health. It also strives to include health considerations in economic, regeneration and urban development efforts.

Heat exhaustion[10]

Heat exhaustion is a phenomenon caused by fluid loss, which in turn causes decreased blood flow to vital organs. Reduced blood flow from heat exhaustion can result in a form of shock. Victims of heat exhaustion often complain of flu-like symptoms hours after exposure.

Heat index[11]

The heat index (HI), given in degrees F, is a measure of how hot it feels when relative humidity (RH) is combined with the actual air temperature.

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.

Heat stroke[12]

Heat stroke occurs when the body's heat regulating mechanisms – including convection, sweating, and respiration – fail. The likelihood of heat stroke increases when air temperatures are higher than skin temperature, and when individuals are low on fluids. Body temperatures can be raised to the point at which brain damage and death can result unless cooling measures are quickly taken.

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).

Hydrological systems

The systems involved in movement, distribution, and quality of water throughout the Earth, including both the hydrologic cycle and water resources.

Hyperthermia[13]

Unusually high body temperature.

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

[9] Definition taken directly from http://www.euro.who.int/healthy-cities on November 21, 2007.

[10] Definition from the U.S. Environmental Protection Agency's Heat Island Glossary, http://www.epa.gov/hiri/resources/glossary.html#h, visited on November 21, 2007.

[11] Defintion modified from NOAA's Heat Index website, http://www.crh.noaa.gov/jkl/?n=heat_index_calculator , visited on November 21, 2007.

[12] Definition from the U.S. Environmental Protection Agency's Heat Island Glossary, http://www.epa.gov/hiri/resources/glossary.html#h, visited on November 21, 2007.

[13] *The American Heritage® Dictionary of the English Language, Fourth Edition*. Retrieved November 21, 2007, from Dictionary.com website: http://dictionary.reference.com/browse/hyperthermia

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*.

Indicator[14]

Information based on measured data used to represent a particular attribute, characteristic, or property of a system.

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,

[14] Definition taken from the Millenium Ecosystem Assessment, Current State and Trends Assessment Glossary, 2005

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*.

IPCC[15]

A panel set up by the United Nations in 1988 to review scientific information on climate change. This panel involves over 2,000 of the world's climate experts. Many of the climate change facts and future predictions we read about come from information reviewed by the IPCC.

K

Kyoto Protocol

The Kyoto Protocol was adopted at the Third Session of the Conference of the Parties (COP) to the *UN Framework Convention on Climate Change (UNFCCC)* in 1997 in Kyoto, Japan. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in Annex B of the Protocol (most member countries of the Organisation for Economic Cooperation and Development (OECD) and those with economies in transition) agreed to reduce their *anthropogenic greenhouse gas* emissions (CO2, CH4, N2O, HFCs, PFCs, and SF6) by at least 5% below 1990 levels in the commitment period 2008 to 2012. The Kyoto Protocol entered into force on 16 February 2005.

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.

Likelihood

The likelihood of an occurrence, an outcome or a result, where this can be estimated probabilistically, is expressed in this Report using a standard terminology, defined in the Introduction. See also *uncertainty* and *confidence*.

Lyme disease

[15] Definition taken from the Climate Change North Glossary at http://www.climatechangenorth.ca/H1_Glossary.html on November 21, 2007.

A vector-borne disease caused by the spirochete Borrelia burgdorferi and transmitted by Ixodes ticks, commonly known as deer ticks. Symptoms include skin lesions, fatigue, fever, and chills, and if left untreated may later manifest itself in cardiac and neurological disorders, joint pain, and arthritis.

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

Nitrogen oxides[16]
Compounds of nitrogen and oxygen produced by the burning of fossil fuels.
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*.

[16] Definition from www.eia.doe.gov/oiaf/1605/95report/glossary.html visited on November 21, 2007.

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.

Particulates
Very small solid exhaust particles emitted during the combustion of fossil and biomass fuels. Particulates may consist of a wide variety of substances. Of greatest concern for health are particulates of less than or

equal to 10nm and 2.5 nm in diameter, usually designated as PM10 and PM2.5, respectively.

Pathogen[17]
An agent that causes disease, especially a living microorganism such as a bacterium or fungus.

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

Photochemical smog
A mix of photochemical oxidant air pollutants produced by the reaction of sunlight with primary air pollutants, especially hydrocarbons.

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.

Q

QALY (Quality Adjusted Life Year)[18]
A measure of the outcome of actions (either individual or treatment interventions) in terms of their health impact. If an action gives a person an extra year of healthy life expectancy, that counts as one QALY. If an action gives a person an extra year of unhealthy life expectancy (partly disabled or in some distress), it has a value of less than one. Death is rated at zero.

Quality of Life[19]
A scientific measure of personal well-being. Categories used to define place-specific quality of life include the inter-related categories of economic conditions; natural resources, environment, and amenities; human health; public and private infrastructure; government and public safety; and social and cultural resources.

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

[17] *The American Heritage® Dictionary of the English Language, Fourth Edition*. Retrieved November 21, 2007, from Dictionary.com website: http://dictionary.reference.com/browse/pathogen

[18] Definition taken from http://www.aihw.gov.au/publications/health/ah96/ah96-x04.html visited on November 21, 2007.

[19] Definition modified from text within Chapter 5 of this document.

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.

Range shifts
Climate change-induced changes in the geographical distributions of plants, animals and ecosystems

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.

Reference scenario
See *baseline/reference.*

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*.

Revealed preference[20]
The use of the value of expenditure to "reveal" the preference of a consumer or group of consumers for the bundle of goods they purchase compared to other bundles of equal or smaller value.

Reservoir
A component of the *climate system*, other than the *atmosphere*, that has the capacity to store, accumulate or release a substance of concern (e.g., carbon or a *greenhouse gas*). Oceans, soils, and forests are examples of carbon reservoirs. The term also means an artificial or natural storage place for water, such as a lake, pond or *aquifer*, from which the water may be withdrawn for such purposes as irrigation or water supply.

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.

Rodent-borne disease[21]
Disease that is transmitted between hosts by a rodent (e.g. bubonic plague, hantavirus).

Runoff
That part of precipitation that does not *evaporate* and is not *transpired*.

S

Salinization

[20] Definition http://www-personal.umich.edu/~alandear/glossary/r.html visited on November 21, 2007.

[21] Definition modified from definition of vector-borne disease.

The accumulation of salts in soils.

Salmonella[22]

There are many different kinds of Salmonella bacteria. They pass from the feces of people or animals to other people or other animals and can cause diarrheal illness in humans. Salmonella has been known to cause illness for over 100 years. They were discovered by a American scientist named Salmon, for whom they are named.

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*.

Smog[23]

[22] Definition modified from information on the CDC's website: http://www.cdc.gov/ncidod/dbmd/diseaseinfo/salmonellosis_g.htm#What%20sort%20of%20germ%20is%20Salmonella visited on November 21, 2007.

[23] Definition from The U.S. EPA's Terms of Environment Glossary at

Air pollution typically associated with oxidants.

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*.

Social indicators[24]

Broad, standardized measures of the quality of life or other socio-economic conditions of geographic areas such as nations, metropolitan areas, or other areas; used to assess health conditions, educational levels, food availability, violence, and other conditions.

Socio-economic scenarios

Scenarios concerning future conditions in terms of population, *Gross Domestic Product* and other socio-economic factors relevant to understanding the implications of *climate change*. See *SRES scenarios.*

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

---

http://www.epa.gov/OCEPAterms/sterms.html visited on November 21, 2007.

[24] Definition from http://srmdc.net/glossary.htm#s visited on November 21, 2007.

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).

Stakeholder

A person or an organization that has a legitimate interest in a project or entity, or would be affected by a particular action or policy.

Stated preference[25]

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

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.

[25] Definition taken from SAP 4.6.

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.

Threshold
The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Time-series studies[26]
Studies done using a set of data that expresses a particular variable measured over time.

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

[26] Definition modified from the definition of time-series data from the Millenium Ecosystem Assessment, 2005.

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). See also *confidence* and *likelihood.*

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*.

United Nations Framework Convention on Climate Change (UNFCCC)
The Convention was adopted on 9 May 1992, in New York, and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilization of *greenhouse gas* concentrations in the *atmosphere* at a level that would prevent dangerous *anthropogenic* interference with the *climate system*'. It contains commitments for all Parties. Under the Convention, Parties included in Annex I aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994. See also *Kyoto Protocol*.

Urban Heat Island Effect[27]
The urban heat island effect is a measurable increase in ambient urban air temperatures resulting primarily from the replacement of vegetation with buildings, roads, and other heat-absorbing infrastructure. The heat island effect can result in significant temperature differences between rural and urban areas.

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

Valley Fever (Coccidiomycosis)[28]
An infectious respiratory disease of humans and other animals caused by inhaling the fungus Coccidioides immitis. It is characterized by fever and various respiratory symptoms. Also called coccidiomycosis.

Valuation[29]
The process of expressing a value for a particular good or service in a certain context (e.g., of decision-making) usually in terms of something that can be counted, often money, but also through methods and

---

[27] Definition from the U.S. Environmental Protection Agency's Heat Island Glossary, http://www.epa.gov/hiri/resources/glossary.html#h, visited on November 21, 2007.

[28] *The American Heritage® Dictionary of the English Language, Fourth Edition*. Retrieved November 21, 2007, from Dictionary.com website: http://dictionary.reference.com/browse/valley fever.

[29] Definition taken from the glossary of the Millenium Ecosystem Assessment, 2005.

measures from other disciplines (sociology, ecology, and so on). See also Values.

Value added
The net output of a sector after adding up all outputs and subtracting intermediate inputs.

Value of a statistical life (VSL)[30]
The sum of what people would pay to reduce their risk of dying by small amounts that, together, add up to one statistical life.

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).

Volatile Organic Compounds (VOCs)[31]
Organic compounds that evaporate readily into the air. VOCs include substances such as benzene, toluene, methylene chloride, and methyl chloroform.

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 consumption
Amount of extracted water irretrievably lost during its use (by *evaporation* and goods production).Water consumption is equal to water withdrawal minus return flow.

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.

Waterborne diseases[32]
Diseases contracted through contact with water that is infected with any of numerous pathogens including *Vibrio cholerae*, *Campylobacter*, *Salmonella*, *Shigella*, and the diarrheogenic *Escherichia coli.*

Watershed[33]
The land area that drains into a particular watercourse or body of water. Sometimes used to describe the dividing line of high ground between two catchment basins.

[30] Definition taken from SAP4.6.
[31] Definition from ATSDR's Glossary of Terms at http://www.atsdr.cdc.gov/glossary.html#G-T- visited on November 21, 2007.
[32] Definition modified from information on CDC's website http://www.cdc.gov/ncidod/dbmd/diseaseinfo/waterbornediseases_t.htm visited on November 21, 2007.
[33] Definition taken from the glossary of the Millenium Ecosystem Assessment, 2005.

Welfare
An economic term used to describe the state of well-being of humans on an individual or collective basis. The constituents of well-being are commonly considered to include materials to satisfy basic needs, freedom and choice, health, good social relations, and security.

Well-being [34]
A context- and situation-dependent state, comprising basic material for a good life, freedom and choice, health and bodily well-being, good social relations, security, peace of mind, and spiritual experience.

West Nile virus[35]
West Nile virus (WNV) is a single-stranded RNA virus of the family Flaviviridae, genus Flavivirus. The main lifecycle of WNV is between birds and insects. Humans are most often infected by a bite from an infected mosquito. Most people infected with WNV don't show any symptoms, whereas those that do are often diagnosed with West Nile Fever which can last up to two weeks.

Z

Zoonoses
Diseases and infections which are naturally transmitted between vertebrate animals and people. See also *zoonotic disease.*

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.

[34] Definition modified from the Millenium Ecosystem Assessment, Current State and Trends Assessment Glossary, 2005

[35] Definition modified from information on http://www.cdc.gov/ncidod/dvbid/westnile/index.htm