environment

A synthesis of potential climate change impacts on the U.S.

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Prepared for the Pew Center on Global Climate Change

by

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

Greenhouse gas emissions—primarily from human activities such as the burning of fossil fuels—are causing changes in the global climate. Global temperatures increased approximately 1°F over the 20th century, and additional warming of 2.5-10.5°F is projected over the next century. The consequences of this warming for the United States will be significant. Natural resources and wildlife are dependent upon climate, as are the economy and human health.

Since 1998, the Pew Center has been chronicling the projected impacts of climate change on important economic sectors, human health, and natural resources. *A Synthesis of Potential Climate Change Impacts on the United States* by Joel B. Smith of Stratus Consulting Inc. is the eleventh in a series of reports examining the potential impacts of climate change on the U.S. environment. This report provides a synthesis of prior Pew Center reports regarding climate change impacts across a number of sectors and regions. This culmination of our Environmental Impacts series is being released with a companion report in our Economics series entitled *U.S. Market Consequences of Global Climate Change*, which provides an in-depth analysis of the market implications of climate change for the U.S. economy. This synthesis reveals:

- ***Natural systems are more vulnerable to climate change than societal systems.*** Species and ecosystems have limited ability to adapt to climate change, and as a consequence, U.S. biodiversity is likely to suffer. Managed sectors such as agriculture and forestry may avoid or reduce some adverse effects of climate change, but this adaptation will not be perfect or cost-free.

- ***Some U.S. regions are more vulnerable than others to climate change.*** The southern United States appears more vulnerable to the adverse effects of climate change than the North, due in large part to its low-lying coastal areas and the sensitivity of southern agriculture and forestry to warmer and dryer conditions. In the North, these sectors may benefit from longer growing seasons, but these benefits may not be sustained at higher magnitudes of warming. Warming may also reduce winter energy costs in the North, but it will increase cooling costs and the risk of heat-related illness and death in northern cities.

- ***Economic studies suggest that the market consequences of low-to-moderate warming will be approximately ±1 percent of U.S. gross domestic product (GDP).*** However, studies also indicate that any net economic benefit of climate change peaks at relatively low levels of warming, beyond which benefits decline and damages begin to accrue.

- ***The rate and magnitude of future climate change will be important.*** Gradual, moderate changes in climate would provide some opportunity for both natural and societal systems to adapt. In contrast, rapid or large changes in climate would increase the risk of large-scale, irreversible disruption of Earth's environment, such as a shutdown of the thermohaline circulation or the collapse of the West Antarctic ice sheet.

Finally, while this series examines the impacts of climate change on the United States, we are mindful that other parts of the world will experience more severe consequences due to their location, physical characteristics, or economic limitations that impair their ability to adapt.

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Executive Summary

Since the 18th century, widespread deforestation and a steady increase in the use of fossil fuels have caused substantial concentrations of carbon dioxide and other greenhouse gases to accumulate in the atmosphere. The warming effect of these gases has caused the global climate to change. Over the past century, average global surface air temperatures increased by 0.6°C (1.1°F). This global warming will continue well into the future, and is likely to accelerate, as long as greenhouse gas concentrations in the atmosphere continue to rise. Although the exact magnitude and rate of future climate change remain uncertain, it will undoubtedly have far-reaching consequences for the United States, its natural resources, and economy.

This report builds on the Environmental Impacts Series published by the Pew Center on Global Climate Change, which reviews the current state of knowledge regarding how climate change will affect a number of economic and natural resource sectors in the United States. Reports in the series have included assessments of how climate change will affect water resources; agriculture and forestry; human health; and terrestrial, aquatic, and marine ecosystems. This report also draws on recent assessments of the potential impacts of climate change on the United States, particularly the U.S. National Assessment and reports prepared by the United Nations Intergovernmental Panel on Climate Change. Recent published literature regarding the implications of climate change for the U.S. economy is also discussed.

While the research completed to date indicates there are substantial uncertainties regarding exactly how climate will change and how it will affect society and ecosystems, it is possible to draw some conclusions about the vulnerability of the United States as a whole and the relative vulnerability of different regions, economic sectors, and natural ecosystems.

1. Natural ecosystems appear to be quite vulnerable to climate change. Climate change threatens to result in the loss of many coral reefs, coastal wetlands, endangered species (particularly those with limited range and mobility), cool- and cold-water fish, and boreal and alpine forest species. In addition, many species associated with particular regions, such as maple trees in New England, may not persevere in their current locations. In general, species are expected to attempt to migrate to higher latitudes or altitudes. This threat to natural ecosystems is distinctly more severe because development has reduced species populations, fragmented ecosystems and placed them under stress from pollution, and introduced barriers to migration, such as communities, farms, roads, and dams. Thus, biodiversity in the United States is likely to be reduced by climate change.

2. A number of sectors of the U.S. economy have a high sensitivity to climate change. Agriculture will be directly affected by changes in temperature and precipitation, and by ensuing effects on the distribution of pests and diseases and availability of water supplies for irrigation. Growth of forests will be sensitive to changes in climate, pests, and disease. Low-lying coastal areas will be at risk from inundation by rising seas. In addition, coastal communities, particularly along the Gulf and East coasts, will face increased risk of inundation, beach erosion, and property damage should the intensity or frequency of coastal storms and hurricanes rise. Human health in the United States will be affected by increased risk of heat stress, decreased risk of some cold weather mortality (although this has not been quantified), potential increases in transmission of infectious diseases, and changes in extreme weather events such as floods. The nation's water resources will be affected by changes in supply resulting from altered precipitation patterns, earlier snowmelt, and increased evaporation. The risks of drought and floods are likely to increase in some areas. In addition, demand for water is likely to change, and may increase in many locations.

3. The capacity of the U.S. economy as a whole to adapt to a limited amount of climate change, with generally small impacts, appears to be quite high. The country's high per capita income, relatively low population density, stable institutions, research base, and health care system give the United States a strong capacity to adapt to climate change. Thus, the country has a relatively large capacity to absorb its adverse effects. This does not mean there will be no cost for adaptation. Indeed, changing water resources management and agricultural practices and protecting coastal areas over this century could cost hundreds of billions of dollars. But, relative to the U.S. economy, these adaptation costs appear to be small and can most likely be absorbed. Finally, the country's large size and the population's mobility give it advantages in adapting to climate change. The lower 48 states span more than 20 degrees of latitude in the temperate climate zone, so while some southern parts of the country are at relatively higher risk from climate change, more northern areas are at less risk or may have many benefits. In addition, the American people are very mobile: in the 20th century there were large migrations to the North (early in the century), the West (throughout the century), and the South (later in the century). In contrast, many developing countries may experience adverse effects from climate change largely because their capacity to adapt to its impacts is limited. Indeed, it is not appropriate to extrapolate the findings for the United States to other countries.

4. Although the nation as a whole has a high capacity to adapt, sectors differ in their vulnerability. Sectors that can change the fastest, such as agriculture, are likely to be able to adapt best to climate change. Sectors with long-lived infrastructure and investments, such as water resources and coastal resources, may have more difficulty adapting and could experience some adverse impacts. However, their ability to adapt to a limited amount of climate change in the long run appears to be high. As noted above, natural ecosystems have a much more limited capacity to adapt to climate change compared to societal sectors, which is exacerbated by development and other human stressors.

5. Different regions of the United States vary in their vulnerability to climate change. The southern United States is, on the whole, more vulnerable than the northern United States. The Southeast and southern Great Plains appear to be the most vulnerable regions because of their low-lying coasts, the potential loss in competitiveness of the agriculture and forest sectors (favorable climate zones for production will shift north), the increased risk of spread of infectious disease (although a strong public health system is likely to contain any potential increase), and especially the potential for reduced water supplies and increased demand for water. This would affect the availability of water for agriculture and instream uses such as protection of aquatic ecosystems. In contrast, northern areas could see mixed effects. While their low-lying coastal areas are at risk from sea-level rise and they (like the rest of the country) would have reduced biodiversity, northern areas could economically benefit from increased agricultural and forestry production and reduced energy costs. As noted below, these economic gains are transient and will not necessarily continue as temperatures keep rising.

6. Even within regions that may have net economic benefits, individual communities and people could be adversely affected. Some populations are at particular risk because their location or vocation exposes them to changes in climate, and their low income constrains their ability to adapt. For example, the elderly poor in northern inner cities are at risk of increased heat stress during more extreme heat waves and generally have limited means of reducing the risk with air conditioning. In addition, many Native American communities may be at risk because they are heavily dependent on natural resources that will be affected by climate change, lack the financial resources to cope, and are not able to easily move to new locations.

7. Studies of the economic impacts of climate change indicate that impacts for a few degrees of warming will be less than ±1 percent of gross domestic product (GDP). These studies attempt to incorporate major market and nonmarket (e.g., biodiversity and quality of life) impacts and assume a gradual change in climate and no change in variability. The direction of impacts (i.e., positive or negative) reported in various economic analyses differs, particularly depending on when the studies were conducted. Economic studies based on impact assessments conducted during the late 1980s and early 1990s tend to show damages of about one percent of GDP. More recent studies that consider new findings on the biophysical impacts of climate change and fully account for the potential for adaptation yield different results. These economic studies suggest that for up to 2-4°C (4-7°F) of warming, there could be net economic benefits of less than one percent of GDP. It is possible that because of factors not considered, such as change in variability or the magnification of impacts across related sectors, or less efficient adaptation than assumed in many recent studies, economic impacts could be more negative than these studies estimate.

8. Economic impacts studies indicate that while there could be benefits, which peak at a few degrees of warming, there would be damages at higher levels of warming. Economic studies indicate that even in those sectors, such as agriculture, estimated to benefit from a small magnitude of warming, benefits peak and subsequently decline. This is because beyond certain increases in temperatures, crop yields decline or the "carbon fertilization" effect, which enables plants to grow more and use less water, saturates at higher carbon dioxide concentrations. In addition, other transient benefits such as reduced energy demand eventually become reversed as costs for cooling rise and savings from less heating are reduced. This is even true for regions such as the northern United States, which may experience economic benefits from a warming of less than several degrees, but losses beyond that. Economic studies suggest that national benefits peak at approximately a 1-2°C (2-4°F) increase in mean temperature. Beyond this, benefits decline until net economic damages occur at a warming of approximately 2-4°C (4-7°F) and become progressively worse with further increases in temperature. Significant uncertainty exists about the level of increased temperature that leads to damages and the magnitude of damages beyond that point.

9. The rate and path of climate change matter. A gradual and monotonic change in climate (e.g., steady increases or decreases in precipitation) will be much easier to adapt to than rapid changes in climate or increased interannual or interdecadal climate variability. In a slowly and steadily changing climate, such adaptations as replacing infrastructure and introducing new technologies can be made gradually. A faster change in climate may necessitate more rapid than normal investments in infrastructure, technology, and other adaptations. Additional risk comes from changes in interannual or interdecadal variability.

10. Increased warming heightens the risk of triggering large-scale changes to the climate system. Substantial increases in global mean temperature can set off large-scale changes to the earth's climate system such as a shutdown of the thermohaline circulation (i.e., the Gulf Stream) or melting of the West Antarctic ice sheet. The thresholds are uncertain (and for some of these events may be quite high), the timeframes of the consequences of such events may take centuries to be fully realized, and the consequences are not well understood. However, it is possible that warming in the 21st century could trigger such events. Once started, they may be extremely difficult, if not impossible, to reverse. The consequences of such events have not for the most part, been studied, but could be substantial.

I. Introduction

Since the 18th century, atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have risen substantially. For example, CO_2 concentrations alone have increased by approximately 30 percent to a present day level of over 370 parts per million (ppm). This is mainly the result of consumption of fossil fuels such as coal, oil, and gas, but it is also the result of deforestation and other activities such as application of fertilizers. The increase in greenhouse gas concentrations has already contributed to a 0.6°C (1.1°F) warming of the Earth's atmosphere since 1900. Over the 20th century, temperatures in the United States also increased by about 0.6°C (1.1°F) and precipitation increased about 5 percent (Karl and Knight, 1998; NAST, 2000).

Greenhouse gas concentrations are projected to continue rising, with CO_2 concentrations projected to reach 500 to 1,000 ppm by 2100. This increase in CO_2 and other greenhouse gas concentrations is projected to raise average global temperatures another 1.4-5.8°C (2.5-10.4°F) by 2100, although the most likely increase in global mean temperature by 2100 is approximately 2-3°C (3.6-5.4°F) (Houghton et al., 2001; Wigley and Raper, 2001; Forest et al., 2002).

The general circulation models (GCMs) used to estimate future changes in the global climate project a wide range of potential changes in U.S. climate, but all show temperatures increasing. On average, the increase in temperature in the United States is estimated to be approximately one-third greater than the increase in global mean temperature (Wigley, 1999). Thus, average temperatures in the United States could increase by about 2-8°C (4-14°F), but the increase will most likely be less than 4°C (7°F). The range of uncertainty is greater for precipitation. Most models show precipitation increasing, but some, such as the Canadian model used in the U.S. National Assessment on Climate Change estimate substantial and even severe droughts in many parts of the country during this century (NAST, 2000).

What does such a change in climate, unprecedented since the dawn of civilization, bode for the United States? Can our society cope with such a change, or will it lead to disruptions such as the mass migration following the Dust Bowl? Are some regions or sectors of the economy more or less vulnerable to climate change?[1] Are natural ecosystems in the United States more or less vulnerable than society? Further, are there thresholds in the magnitude or rate of climate change to which the United States can adapt?

This report synthesizes what is known about the effects of climate change on the United States by examining literature on the relative vulnerability of sectors and regions and considering whether, as higher concentrations of greenhouse gases are reached, positive impacts become negative or negative impacts become more adverse (i.e., whether the character of impacts changes at different magnitudes of climate change). The report briefly reviews what is known about climate change, then discusses key uncertainties and limitations regarding our knowledge about its impacts on the United States. Rather than merely repeating what has been covered in the other reports in the Pew Center's Environmental Impacts series, this report synthesizes the literature on impacts by comparing the relative vulnerability of sectors to climate change. The final section of the report reviews the literature on estimated monetary damages to the United States from climate change.

The report draws on two main sources of information. The first is the series of impacts reports published by the Pew Center on Global Climate Change. This series discusses the state of knowledge about the science of climate change and its impacts on key sectors:

- Science (Wigley, 1999)
- Agriculture (Adams et al., 1999a)
- Water resources (Frederick and Gleick, 1999)
- Sea-level rise (discussed here as coastal communities) (Neumann et al., 2000)
- Natural terrestrial ecosystems (Malcolm and Pitelka, 2000)
- Human health (Balbus and Wilson, 2000)
- Aquatic ecosystems (Kennedy et al., 2002; Poff et al., 2002)
- Forestry (Shugart et al., 2003)
- Coral Reefs (Buddemeier et al., 2004)
- Adaptation (Easterling et al., 2004)

The second source is literature that has become available since these reports were published. The discussion on affected sectors and regions is limited to the sectors listed above.

This report also examines the literature on estimates of aggregate monetary damages to the United States. A number of such estimates were developed in the early 1990s, based on the U.S. Environmental Protection Agency's report on *The Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989). These estimates have been updated, drawing on more recent assessments of potential impacts, such as Mendelsohn and Neumann (1999), the U.S. National Assessment (NAST, 2000), and Mendelsohn (2001). The report reviews these new estimates and examines their strengths and weaknesses.

II. Key Findings on Vulnerability in the Pew Center's Environment Series

The ten reports currently within the Pew Center's environment series address the implications of climate change across a broad range of economic sectors and natural ecosystems. A number of key findings emerge from these reports regarding the vulnerability of sectors and ecosystems in the United States:

- ***Natural ecosystems, such as forests and estuaries, are in general more vulnerable to climate change than societal sectors, such as agriculture and coastal development.*** Generally, natural systems appear to be much more vulnerable to climate change because they have less capacity to adapt. Natural systems must rely on their own natural abilities to cope with climate change and, in many cases, the rate of climate change will exceed the ability of these systems to adapt. In addition, pressures from development and other human stresses will make adaptation more difficult. In societal sectors, however, financial resources can be applied, technology can be developed, and other changes can be made to help affected systems adapt to climate change.

- ***Vulnerabilities differ across regions.*** A number of studies have shown that regions bear different risks from climate change. Some regions can benefit, while others can be harmed.

- ***Climate change interacts with other stresses.*** The presence of other stresses such as pollution can exacerbate the risks of climate change. For example, growth of populations living in low-lying coastal areas increases the exposure of people and property to sea-level rise. Additional habitat fragmentation and pollution further weaken the ability of natural systems to adapt to climate change.

- ***Adaptation can offset many adverse effects of climate change.*** Adaptation, particularly in societal systems, can offset many adverse effects of climate change, even reversing some. Planning for future changes in climate can further reduce vulnerability.

• ***Greater levels of climate change or more rapid climate change increase vulnerability.*** The impacts of climate change are more likely to be negative at higher magnitudes of warming. This is because greater climate change can result in more adverse effects or exceed thresholds beyond which gains from smaller amounts of climate change are lost and damages occur. Many systems, particularly societal systems, appear to be able to adapt to gradual rates of climate change. More rapid rates of climate change are more likely to exceed the capability of many systems to adapt.

III. Key Uncertainties and Limitations

Our understanding of the potential impacts of climate change on the United States has improved substantially over the last two decades, but many critical uncertainties still remain about climate change itself as well as its impacts. These uncertainties include the following:

1) Regional climate change. As noted above, there is substantial uncertainty about how regional climates will change and about many regional impacts of such change. This is particularly the case with changes in regional precipitation, about which climate models disagree quite dramatically. Different regional or even national patterns of climate change can result in very different estimations of impacts. For example, Malcolm and Pitelka (2000) note that under different estimates of changes in precipitation in the Deep South, there are different estimates of change in net primary productivity (the amount by which plants grow in a year) of vegetation in the region, with some scenarios showing decreases and others showing increases.

2) Change in climate variability. Most studies of climate change impacts (e.g., Smith and Tirpak, 1989; Mendelsohn and Neumann, 1999; Mendelsohn, 2001) assume changes only in average climate conditions, not in climate variability. Such studies include changes in extreme events, such as more intense precipitation events and heat waves, because mean temperature and, in many cases, mean precipitation are assumed to rise. The typical approach in such studies is to add a mean change to a historic record. So an average 2°C (4°F) warming would raise all temperatures in the record by 2°C, including historic high temperatures. But these studies do not address other changes in variability, such as increases in the frequency and intensity of storms, hurricanes, or El Niños. Changes in variability could have a substantial effect on estimated impacts, with increased variability resulting in more adverse effects. For example, Rosenzweig et al. (2000) point out that interannual crop yield variability has increased in recent years, indicating that agriculture's sensitivity to climate variability and changes in variability may be increasing.[2]

3) Carbon fertilization. One of the key uncertainties about how biophysical systems will respond to climate change concerns the carbon fertilization effect. Laboratory and field experiments (e.g., DeLucia et al., 1999) have demonstrated that higher CO_2 concentrations increase plant growth and decrease plants' demand for water—an effect referred to as CO_2 fertilization. When CO_2 fertilization is not included in models estimating changes in terrestrial vegetation, including agriculture, declines in yield or biomass are estimated because climate change alone can result in drier conditions or cause plants to exceed their thermal tolerances. However, when CO_2 fertilization is included, growth is estimated to be greater and plants are estimated to demand less water. The long-run and ultimate effects of CO_2 on biomass are uncertain (Rosenzweig and Hillel, 1998), but recent work demonstrates that the positive effects of CO_2 in the field may be less than laboratory experiments suggest. In addition, the growth appears to be mainly in twigs and litter rather than in main stems or branches (e.g., Schlesinger and Lichter, 2001).

4) Societal development. Economic development can affect the vulnerability of societal systems (e.g., agriculture, water resources) and natural ecosystems to climate change (Smit and Pilifosova, 2001). Increased human population and economic activity can increase the number of people and property exposed to extreme events (e.g., more coastal development can put more people and property at risk from sea-level rise and coastal storms; Neumann et al., 2000); increased wealth and technology can also reduce vulnerability by providing financial resources for adapting to climate change and technology to predict and adapt to climate change effects.

5) Adaptation. A critical factor affecting estimates of climate change impacts are the assumptions made about adaptation. Adams et al. (1999a) and Neumann et al. (2000) discuss how different assumptions about adaptation in agriculture and coastal resources can substantially change the magnitude if not the direction of estimated changes in those sectors (see also Tol et al., 1998). Assumptions about decisionmakers having perfect foresight and access to information and behaving in an economically "rational" manner can substantially reduce estimates of damages (see Easterling et al., 2004).[3] In addition, the literature tends to assume a "smooth" and monotonic change in climate, which would make adaptation easier. A more erratic change in climate, such as more intense extreme weather events, would make adaptation more challenging (West and Dowlatabadi, 1999). More extreme wet or dry years or decades may cause people to adapt to one set of conditions, only to be caught off-guard when conditions change (see Reilly and Schimmelfennig, 1999).[4] Finally, the costs of adaptation are not accounted for in studies of some sectors (e.g., agriculture) or are assumed to be virtually costless (e.g., capital affected by climate change will be replaced as its useful life expires, thus minimizing expenditures).

6) Omitted impacts. Some potentially affected sectors such as tourism and recreation have received limited attention in the literature.[5] Given their large economic size, changes in these sectors could have a substantial economic impact. For example, 7 percent of the U.S. economy is devoted to tourism (U.S. BEA, 2002c). Some studies of aggregate economic impacts of climate

Box 1

What We Know About Climate Change That Enables Us to Identify Relative Vulnerabilities

While there is substantial uncertainty about many aspects of climate change, there are two things about the nature of climate change and how systems will respond to it that enable us to determine which sectors and regions are relatively more or less vulnerable. First, since we know temperatures will rise, we know that climate zones will shift toward the poles and higher altitudes. This means that many human activities and natural systems strongly influenced by climate are likely to shift latitude and altitude as well. We expect agriculture and forestry to shift northward in the United States, just as we expect terrestrial and aquatic species to migrate northward or toward higher altitudes. A northward or higher altitude shift does not imply that the low latitudes and altitudes will be devoid of climate-sensitive economic activities or biodiversity. New activities or species, better adapted to warmer temperatures, are likely to be adopted or to migrate into these areas. But the location of activities and species will change. Analysis shows that southern areas are at greatest risk of losing output in such climate-sensitive activities as agriculture and forestry, while northern areas could increase output in those sectors.

Second, the rate at which systems can change location or behavior in response to climate change in many ways determines their vulnerability. McCarthy et al. (2001) state that a system's vulnerability to climate change is determined by the exposure of that system to climate change (i.e., how much climate changes), the system's sensitivity to it (how much it can affect the system), and the system's ability to adapt. What differentiates the vulnerability of human systems from natural ecosystems, particularly in a wealthy and highly mobile country such as the United States, is the much greater ability of human systems to adapt to climate change. It is quite conceivable that agriculture, forestry, water resources, coastal communities, and other sectors of society will adapt through prevention (e.g., sea walls) or adjustment of behavior (conserving water, building new infrastructure, or changing location of activities). In contrast, the ability of many species to adapt to climate change will be limited by their capacity, for example, to migrate to new locations, because many species cannot migrate in pace with climate change. In addition, migration will be limited by human development, which creates barriers to migration, fragments ecosystems, and introduces stresses through pollution and other activities. Since we are confident about the relative ability of human and natural ecosystems to adapt to climate change, we are confident that natural ecosystems are much more vulnerable to climate change than human systems in the United States.

change (e.g., Nordhaus and Boyer, 2000, which is discussed below) estimate that the magnitude of economic impacts in these sectors could be greater than the magnitude of impacts in sectors that have been studied in more depth.

7) Rapid or catastrophic changes in climate and impacts. The consequences of a rapid change in climate or increased climatic variability have received little attention in the literature.[6] For example, the consequences of potentially catastrophic events such as rapid deglaciation, changes in ocean circulation, or positive greenhouse gas feedbacks have not been thoroughly investigated. In addition, impact studies have not considered a confluence of adverse impacts resulting from climate change, such as increases in drought, health risks, and storms. The ability of society to cope with a confluence of such events is not certain, nor is the probability that many of these events will occur.

While there is extensive literature on climate change impacts in the United States, there is still uncertainty because of these key factors. We are not yet able to predict the exact impacts of climate change. However, we are improving our understanding of the sensitivity of societal and natural systems to changes in climate. Based on this knowledge, we are able to draw some conclusions about the potential direction of changes in many systems and the relative vulnerability across systems and regions. The reasons why we can make such projections are discussed in Box 1.

Box 2

Vulnerability of Developing Countries

The impacts of climate change on developing countries are likely to be negative, even at lower levels of warming (e.g., McCarthy et al., 2001). Low-latitude developing countries appear to be much more vulnerable to climate change than high-latitude developed countries for two reasons. First, a warmer climate presents risk to the warmest regions of the world. Studies of global agriculture have consistently found that production in low-latitude countries could decrease (e.g., Rosenzweig and Parry, 1994; Darwin et al., 1995), which increases the risk of malnutrition. Risks of adverse health effects are greater in low-latitude countries because they are unlikely to benefit much from reduced cold weather deaths, but could face greater risk from heat stress and infectious diseases—risks that are generally exacerbated by higher temperatures (see Balbus and Wilson, 2000).

Second, developing countries have a lower capacity to adapt to climate change than developed countries because they tend to have lower per capita income, a higher percentage of their economies in climate-sensitive activities, and, in many cases, inadequate institutions compared to developed countries (see Smit and Pilifosova, 2001). For example, they will have less financial and technical capacity to make adaptations in agriculture or water resources. The risk from climate change to public health in developing countries is greatly exacerbated by the inadequacy of their public health systems (McMichael and Githeko, 2001; Tol and Dowlatabadi, 2002). This combination of increased sensitivity and lower adaptive capacity puts the low-latitude developing countries at greater risk from climate change. Furthermore, the United States could be affected by impacts in developing countries through changes in the need for international aid and through a higher influx of refugees into the country.

IV. National Impacts by Sector

This section summarizes information on national impacts of climate change. It addresses societal sectors (i.e., sectors heavily managed by society) such as agriculture, water resources, and forestry, and natural sectors such as terrestrial ecosystems and aquatic ecosystems. In general, societal sectors in the United States are less vulnerable to climate change than natural sectors because the societal sectors have much greater capacity for adaptation.

A. Agriculture

Agriculture is highly sensitive to climate change, but this sector also possesses a substantial capacity to adapt. Crop yields are likely to be greatly affected by climate change. Changes in temperature, precipitation, and CO_2 concentrations can result in large reductions in growth and water use of some crops and large increases in others. This depends on many factors, including the crops themselves (some are more sensitive to changes in temperature or CO_2 levels than others) and locations (grain crops in more northern locations are more likely to benefit from additional heat, while crops in more southern locations are more likely to have reduced yields).

Agriculture has a significant capacity to adapt to climate change for two reasons. First, agricultural systems can be quickly changed in response to external factors such as change in climate. Second, agriculture is part of a market system. Markets are self-equilibrating because they send signals to producers and consumers about scarcity or abundance of resources. If climate change causes yields to decrease, prices will increase, leading to more production and less demand. If climate change causes yields to increase, prices will fall, leading to less production and more demand.

These two factors combine to substantially moderate the effects of large changes in crop yields. Adams et al. (1999a) found that a temperature increase up to 2-3°C (4-5°F) is unlikely to have a significant effect on U.S. agricultural production. Indeed, national production could increase. This is the result of a number of factors, including increased grain yields in the North offsetting reduced grain yields in the South and the ability of agriculture to adapt by introducing new crops and shifting production to areas that become more favorable for crops.[7] Agricultural output is estimated to peak at a temperature increase of about 2-3°C (4-5°F) and then start declining. Beyond approximately 5°C (9°F), national agricultural production could fall below current levels as a result of the CO_2 effect becoming saturated at higher CO_2 concentrations and increased stress on plants from higher temperatures. Assumptions about the efficiency of adaptation are critical for explaining differences in estimated changes in production among agriculture modeling studies. While agriculture studies have addressed what may happen to production, they have not assessed the costs of making adaptations (e.g., introducing and switching crops, redesigning and relocating infrastructure). They also assume that the adaptations are appropriate, efficient, and effective. In addition, these analyses incorporate optimistic assumptions about CO_2 fertilization. Some of the studies incorporate potential changes in water supplies, while others do not. Also, the studies have not addressed the potential impacts of changes in climate variability or flooding (Rosenzweig et al., 2000; Rosenzweig et al., 2002).

While national production may not be significantly affected, there could be large regional changes in agriculture. The Southeast and Southern Great Plains may lose competitive advantage, while more northern areas such as the Midwest and Northern Great Plains could benefit. For example, Adams and McCarl (2001) found that under most of the scenarios they examined, northern agricultural producers had increased output, while southern producers had decreased output. Mendelsohn (2001) found similar results.

B. Water Resources

Although water resources, which are also quite sensitive to climate, have a high potential capacity to adapt, long-lived infrastructure and institutional issues are likely to combine to make adaptation in this sector more challenging than in sectors such as agriculture.

Water resources will be directly affected by climate change through changes in precipitation, evaporation, and snowmelt. While, on average, global precipitation will increase, some areas could see less precipitation, and seasons could be affected differently (e.g., more winter precipitation and less summer precipitation). Temperatures will rise everywhere in the United States, resulting in earlier snowmelt and more evaporation. More frequent and intense floods and droughts are possible. Thus, some regions could benefit from increased supplies, but could face risks from increased flooding. Others could see increased droughts and floods (Frederick and Gleick, 1999).

The United States has been successful in adapting to quite different hydrologic conditions, ranging from the relatively wet Northeast to the relatively dry Southwest. But it has done so by optimizing infrastructure and institutions such as water laws for current hydrologic conditions. A significant change in climate could make substantial investments in infrastructure or changes in water use patterns and legal arrangements necessary.[8] The time and expense involved in modifying existing infrastructure or building new infrastructure, and the political difficulties involved in changing water laws and other institutional arrangements concerning production and use of water resources could make adaptation of water resources much more challenging than in sectors such as agriculture.

All regions could face risks from changes in water supply and water quality. The Southwest appears to have the greatest sensitivity to changes in water supply because supplies there already are limited. The southern half of the United States has the greatest sensitivity to changes in water quality for a number of reasons, including the already low dissolved oxygen levels, relatively high presence of endangered species, and high sensitivity to low-flow conditions (which is mainly in the Southwest; Hurd et al., 1999).

C. Coastal Communities

Sea-level rise threatens to inundate and erode many low-lying coastal areas. The Southeast and mid-Atlantic coasts are the most vulnerable to sea-level rise because they are low-lying, heavily developed in many areas, and at greatest risk from increased hurricane activity. Parts of the Northeast are also vulnerable because they are low-lying and heavily developed. The West Coast is less vulnerable because a large portion of it is made up of rocks or cliffs. However, low-lying areas and bays such as Puget Sound, San Francisco Bay, and much of Southern California are vulnerable to inundation from sea-level rise (Neumann et al., 2000).

Highly developed coastal areas are likely to be protected from sea-level rise because the costs of protection are lower than the value of property at risk. However, sea-level rise will result in higher infrastructure costs to protect at least some developed coastal areas and in inundation of many unprotected coastal areas. Estimates of the total undiscounted financial costs of adapting to a 0.5 meter sea-level rise (roughly the best estimate of eustatic sea-level rise by 2100; Wigley, 1999; Houghton et al., 2001) range from $20 billion to $138 billion. This includes building coastal defenses to protect high-value areas and abandoning property in low-value areas (Neumann et al., 2000). The difference in estimates is mainly the result of different assumptions about adaptation. The low estimates assume an economically efficient response (areas are protected when benefits exceed costs and property owners allow properties to depreciate before being inundated), and the high estimates assume that all developed coastal areas will be protected from sea-level rise. Damages will increase with higher magnitudes of sea-level rise. Total (undiscounted) infrastructure costs to protect developed areas from a one meter sea-level rise are estimated to range from $36 billion to $321 billion (Neumann et al., 2000). These estimates do not consider potential changes in storm or hurricane frequency and intensity; more intense hurricanes would increase risk to life and coastal property.

D. Human Health

Human health is highly sensitive to climate change, but the nation's wealth and its strong public health system will likely prevent any significant human health problems. Increased flooding, hurricanes, and coastal storms could put more people at risk of injury or death. Heat stress mortality is expected to increase (although increased use of air conditioning can partially offset this), and there could be isolated outbreaks of infectious diseases. Low-income elderly residents of inner cities in the Northeast and Midwest are at greatest risk of heat stress, and increased risk of dengue fever may be greatest along the Rio Grande. However, the complex and nonlinear nature of infectious disease makes it very difficult to predict changes in frequency and location of outbreaks. Should new diseases be introduced, risks may be higher because it may take longer to recognize the presence of the disease and to develop effective preventive measures. Air quality could also deteriorate, particularly if ozone precursors are not further reduced. Cold weather related mortality could decrease, but it is not known whether such a decrease could offset increased mortality from heat stress. Maintaining the public health infrastructure, particularly its capability to monitor for outbreaks of diseases and to intervene when necessary, is a very important factor that may minimize risk of climate change to human health. The costs of maintaining public health under more adverse climate conditions have not been estimated (Balbus and Wilson, 2000).

Should the rise in temperature be at the upper end of the forecast range in the 21st century or should temperatures continue to rise beyond that, the risks to human health are likely to be greater. The potential for increases in extreme events rises with higher magnitudes of climate change. As average temperatures increase, the potential for more extreme heat waves also rises (Wigley, 1999). Furthermore, at greater magnitudes of climate change there is greater potential for disruption of ecosystems, which could increase the risk of infectious disease outbreaks.

E. Terrestrial Ecosystems

Substantial changes in the distribution of ecosystems in the United States are likely under climate change, with a general shift in species to the north and to higher altitudes, and the potential for the outright elimination of some ecosystems, especially those currently in colder locales. Climate change will result in a northward or higher altitude shift of climates that species can survive in or are best adapted to. To survive climate change, species will need to migrate because new climates may be beyond their tolerance or may bring competitors, predators, diseases, or other changes that would threaten their survival.

Ecosystems do not migrate as a whole. Instead, individual species migrate—typically at different rates. New ecosystems are likely to involve different assemblages of species. Disturbances such as fire, disease, or drought are likely to play a critical role in changing the location of species (e.g., Parsons et al., 2003). Many species may be unable to migrate in pace with shifting climate zones, may find paths of migration blocked by natural or artificial barriers, or may find themselves outcompeted by invasive species. Even those species that are able to migrate in pace with climate change are likely to encounter other species with which they have not previously interacted. How individual species will respond to novel predator-prey, competitive, symbiotic, or parasitic relationships is largely unknown and difficult to predict. Beyond this, the risk to natural ecosystems from climate change is far more serious because development has put ecosystems under stress through habitat destruction, fragmentation, and pollution. Thus climate change is expected to exacerbate the loss of biodiversity already resulting from development in the United States.

On the other hand, the productivity of terrestrial vegetation in many parts of the United States may increase. Net primary productivity has been estimated to remain the same or increase up to one-third with a doubling of CO_2 concentrations (Malcolm and Pitelka, 2000). These estimates are based in part on the assumption that the CO_2 fertilization effect will be fully realized and persistent in natural conditions. However, increased fire frequency and respiration could offset these gains in vegetation productivity. In addition, should the effect of CO_2 on vegetation be less positive, the net effects of climate change on terrestrial ecosystems would be less positive or even negative (Malcolm and Pitelka, 2000).

The response of ecosystems is likely to differ from east to west. In the eastern two-thirds of the country, the expected response is a northern shift in location. Parts of the Deep South and upper Midwest could have reduced vegetation productivity. In the western third of the country, mountains may enable species to migrate upslope and provide a north-south corridor. The mountainous topography of the West also means there are many microclimates and barriers to migration—both of which combine to isolate species and inhibit migration. Alpine systems may not survive in the lower 48 states.

As greenhouse gas concentrations continue to increase, there is a greater likelihood of increasingly negative impacts on terrestrial ecosystems. The CO_2 fertilization effect will begin to saturate and the inevitable higher temperatures could cause more stress on species, particularly if precipitation does not increase substantially. Indeed, should temperatures reach the upper end of the projected range in the 21st century, negative effects on most terrestrial ecosystems are likely, particularly if precipitation amounts do not change or decline (Malcolm and Pitelka, 2000; Bachelet et al., 2001).

F. Forestry

The location, composition, and abundance of U.S. forests will be altered substantially under climate change, although actual changes will be dependent on future trends in temperature and precipitation and on the ultimate effects of CO_2 fertilization. Generally, forests will move northward and to higher altitudes, following the same pattern as other terrestrial ecosystems. As with other forms of vegetation, rates of migration are limited and may not keep up with shifts in location of suitable climate zones. Plantation forests may fare much better because they are managed; spacing and rotation periods can be adjusted to account for climate change, and species can be substituted after a harvest with more suitable trees for future conditions.

As with agriculture, while there may be substantial differences in how regional forests will be affected by climate change, most economic studies find that the effects on the U.S. forest industry will be relatively small. Gains in one region can offset losses in another. Northern areas are likely to benefit either because yields of species grown there could increase or because more valuable Southern species can be planted in the North. The impacts on Southern and Northwestern forests are mixed: in some scenarios, Southern and Northwestern producers gain, while in others they lose. How the U.S. forest industry fares as a whole depends on a number of factors. Should there be an increase in productivity, consumers will benefit from lower prices, but the industry could be hurt by falling prices unless demand (particularly foreign demand) increases substantially. Should there be decreased yields, the industry would benefit from higher prices, but consumers would be harmed. However, if substitutes for wood become readily available, the industry would be harmed because consumers will start using substitutes, which will keep prices from rising as much as they would otherwise. In addition, the effects of climate change on foreign producers are important. Should forest productivity abroad increase, there could be more imports, benefiting consumers but harming the domestic forest industry (Sohngen et al., 2001; Shugart et al., 2003).

G. Aquatic Ecosystems

Climate change will greatly alter the character of aquatic ecosystems and could have many adverse effects. As with terrestrial ecosystems, climate zones and habitats will generally shift northward. A critical issue is the ability of populations to migrate to new locations. The larger and deeper the water bodies, the more feasible it is for species to migrate. Smaller lakes, rivers that do not run north-south or from sufficiently high altitudes, dams, and even some estuaries may block or impede migration to new habitats. Different species have different capabilities to migrate, and new assemblages of species are highly likely. As with terrestrial ecosystems, the greater the impact of development on ecosystems, the more likely it is that the additional impacts of climate change will be negative. Effects will vary, depending on whether freshwater, estuarine, or marine impacts are being considered.

While many warm-water fishes could benefit from lakes and streams becoming more suitable for their survival, cool- and cold-water fish such as trout would find fewer lakes and streams to inhabit. Changes in runoff due to earlier snowmelt and changed precipitation patterns could adversely affect many fishes. Impacts on wetlands will vary depending on types of wetlands, topography, and whether conditions become wetter or drier. Increased summer drought might eliminate or severely contract small wetlands important for migratory waterfowl.

Coastal ecosystems could be harmed if sea levels rise faster than wetlands can accrete sediments or if inland migration of wetlands is blocked. Mangroves may move into southern areas, and the productivity of estuarine ecosystems would be affected by changes in salinity resulting from the combination of sea-level rise and changing runoff. Changes in runoff and winds will also affect circulation in estuaries and aquatic productivity (Poff et al., 2002). In addition, 20 to 45 percent of coastal wetlands could be inundated by a 0.5 meter sea-level rise if developed areas are protected (Titus, 1992), with substantial harm to estuarine ecosystems (Neumann et al., 2000). With a 1 meter sea level rise, 29 to 69 percent of U.S. coastal wetlands would be inundated (Titus, 1991). The value of these ecosystem impacts is not included in damage estimates.

On the whole, climate change may have more modest effects on open ocean ecosystems than on estuarine or freshwater systems. Limited analysis suggests that productivity of the world's oceans could decline. However, high-latitude areas could benefit. Depending on location, the productivity of oceans is likely to be affected by changes in temperature, the frequency and intensity of events such as the El Niño/ Southern Oscillation and the North Atlantic Oscillation, and changes in circulation such as the thermohaline circulation (which includes the Gulf Stream). Many of these changes are currently difficult to predict.

Coral reefs are likely to be harmed by higher temperatures. Many reefs are already being damaged by high sea-surface temperatures caused by El Niño events (e.g., Gardner et al., 2003). In addition, higher atmospheric CO_2 levels reduce calcification in coral reefs, limiting their ability to grow and expand (Kennedy et al., 2002; Buddemeier et al., 2004).

V. Synthesis of National Impacts

In general, natural ecosystems appear to be at much greater risk from climate change than societal systems such as agriculture and forestry. This is because ecosystems have much more limited adaptive capacity than societal systems, particularly societal systems in a developed country. For societal systems, humans can invest in the development of new technology and infrastructure, change practices and methods, or migrate to new locations, all of which can increase the resiliency of societal sectors to climate change. In contrast, many animal and plant species have much less capacity to adapt to climate change than society, particularly a rapid change, because they cannot migrate, change behavior, or evolve rapidly with climate change.

Figure 1 displays the estimated direction of national-level changes by sector, i.e., whether impacts are "positive" or "negative." Note that terrestrial biodiversity is treated separately from terrestrial ecosystems because the sensitivities appear to be different; there may be positive impacts in one and negative in the other. To be sure, what is positive or negative is a matter of judgment, but the labels here are associated with whether the sector is more or less productive or provides more or fewer services under climate change. With a warming of less than a few degrees Celsius, the effects on sectors would be mixed. Coastal communities, terrestrial biodiversity, and aquatic biodiversity would be adversely affected. In contrast, agriculture and forestry could benefit because CO_2 fertilization is estimated to generally offset the negative direct effects of warming and because the sectors have high adaptive capacity. The CO_2 effect could also increase the productivity of terrestrial vegetation. How water resources across the country will be affected by a few degrees of warming is uncertain. This is mainly because of uncertainty about changes in regional precipitation. However, earlier snowmelt, more intense precipitation, and increased adaptation costs can cause adverse impacts in many regions. Net health effects are uncertain, but the magnitude of impacts may be small.

While impacts may be small or benign with a few degrees of warming, more negative effects are anticipated as greenhouse gas concentrations increase and drive temperatures higher. Higher temperatures are likely to impose stress on vegetation. In addition, higher atmospheric concentrations of CO_2 are more likely to be combined with even higher temperatures. This could lead to negative effects on agriculture, forestry, and terrestrial ecosystem productivity. Higher temperatures and sea-level rise would cause more adverse effects on coastal communities and aquatic and terrestrial biodiversity. Impacts on human health are uncertain, but at higher temperatures, there is more potential for extreme climate events, which would cause more negative impacts. If temperatures rise more rapidly than predicted for the 21st century, adaptation will become more difficult. Although there is less confidence in findings regarding water resources, they could experience net adverse impacts from higher temperatures, more substantial precipitation changes, and higher adaptation costs.

Figure 1

Summary of National Impacts by Sector and Extent of Temperature Change

	Sector							
Change in Temperature	**Agriculture**	**Water**	**Coastal Communities**	**Health**	**Terrestrial Ecosystem Productivity**	**Terrestrial Biodiversity**	**Forestry**	**Aquatic Biodiversity**
< Few degrees of warming	⇑ Med	?	⇓ High	⇔ Med	⇑ Low-Med	⇓ Med	⇑ Low-Med	⇓ Low
> Few degrees of warming	⇓ Low-Med	⇓ Low	⇓ High	?	⇓ Low-Med	⇓ High	⇓ Low	⇓ Med

Notes: ⇑ indicates positive effects such as increased productivity

⇓ indicates negative effects such as net damages or reduced productivity

⇔ indicates mixed effects, i.e., positive and negative

? indicates uncertainty about the direction of change

The size of the arrow is related to the magnitude of the effect

Low, medium, and high are the levels of confidence in the direction of change

VI. Regional Impacts

Regional vulnerability to climate change differs: southern areas generally are more vulnerable than northern areas to the effects of climate change. This section addresses how vulnerabilities might differ among the six regions of the continental United States displayed in Figure 2: Northeast, Southeast, Midwest, Southern Great Plains, Northwest, and Southwest. Regional differences in sensitivity to climate change are further complicated by a significant variance in sensitivity within many of the regions. The discussion below addresses the average impacts of climate change on U.S. regions. Within these regions, there are likely to be variations in how states, counties, cities and towns, and individuals will be affected by climate change.

A. Northeast

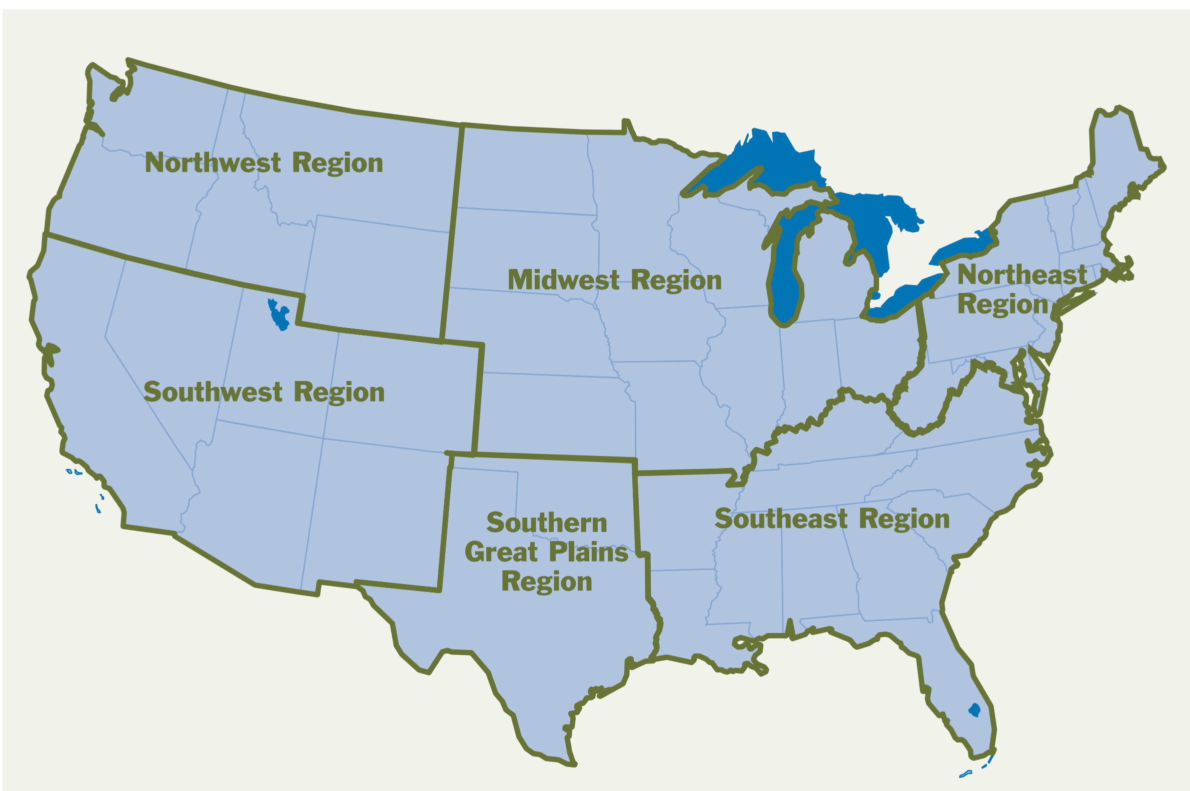
While the Northeast is a relatively cold region that could benefit from warmer temperatures, there appear to be mixed effects across sectors. Its generally low-lying coast makes the region vulnerable to sea-level rise. By destroying coastal wetlands, sea-level rise could be harmful to highly productive estuaries such the Chesapeake Bay. Human health impacts include heat stress mortality, which could increase in large urban areas such as New York City and Philadelphia, although deaths from cold weather could decrease.[9] Infectious disease is not expected to be much of a problem in the Northeast, but occasional outbreaks could happen. It is likely that such outbreaks would be controlled. It is uncertain how agriculture will fare; some studies have found that agricultural production in the region could decline (e.g., Adams and McCarl, 2001), while others estimate potential increases in production (e.g., Mendelsohn et al., 1999). Forest productivity could increase in the region, but valuable species such as maples may eventually disappear. Also, stocks of cool- and cold-water fish may decrease, but stocks of warm-water fish may increase. Compared to water supplies in warmer and drier regions, the Northeast's supplies are relatively less vulnerable to small changes in average climate conditions (Hurd et al., 1999). Net changes are uncertain (NAST 2000). The region's ski and winter sports industry may be harmed, but warm weather recreation activities may increase.

B. Midwest

The Midwest, which includes the northern Great Plains in this report, is another relatively cold region that could have a combination of benefits and adverse impacts from warmer temperatures. Studies of economic impacts on U.S. agriculture tend to show the Midwest as one of the regions most likely to see increased production (Adams and McCarl, 2001). Productivity of Midwestern forests may also increase, although some studies show the potential for decreases in vegetation productivity in the region (Malcolm and Pitelka, 2000). On the other hand, a rapid change in climate could decrease biodiversity, adversely affecting such valuable habitat as the Prairie Potholes (a region of wetlands in the upper Midwest). Impacts on water resources could be mixed. Increased precipitation in the northern part of the region could result in more runoff, but also more flooding. Some studies estimate that Great Lakes levels could decline (e.g., Chao, 1999), but ice cover would be reduced. Summer drought could increase in many parts of the region.

Figure 2

Regions of the United States



There may be a decrease in stocks of cool- and cold-water fish, but an increase in warm-water fish. As in the Northeast, heat stress mortality in urban areas could increase. The 1995 heat wave in Chicago, which resulted in hundreds of deaths (Whitman et al., 1997), demonstrated that urban areas in the region are highly sensitive to extreme heat. As in the Northeast, risks of outbreaks of infectious disease appear to be low.

C. Southeast

The Southeast appears to be relatively more vulnerable to climate change across most affected sectors. As noted above, the region is the most vulnerable to sea-level rise because of its low-lying coast and heavy development in many areas (see Neumann and Livesay, 2001). Should hurricane intensity increase, the risk to the region would be greater (Neumann et al., 2000). The region contains most of the nation's coastal wetlands; Louisiana alone has 40 percent (Neumann et al., 2000), and inundation of many of these wetlands would reduce productivity and diversity in the region's estuaries. Higher temperatures would reduce water quality in the region. Water supplies, which are tight in many places, would be at risk should runoff decrease. On the other hand, increased runoff would likely heighten flooding risks. Agriculture could be harmed by a loss of competitive advantage to more northern areas, although citrus crops may have reduced risk of freezes and other warm weather crops could benefit. The Mississippi Delta states may face larger reductions in agricultural output relative to the rest of the region. It is possible that forest productivity could decline in the Deep South but increase in the upper South. Northward shifts of habitats for some important timber species such as loblolly pine and slash pine are likely (Shugart et al., 2003). Interestingly, the region is at relatively low risk for increased heat stress mortality, because variation of daily summertime temperature is low and there is higher use of air conditioning. The warm and wet conditions make it potentially more susceptible to outbreaks of infectious disease, but a strong public health infrastructure may keep such risks low.

D. Southern Great Plains

The Southern Great Plains, consisting of Texas and Oklahoma, could also experience many negative impacts of climate change because of its low latitude and aridity. The low-lying Texas coast is at risk from sea-level rise, although the risk is lower than in the Southeast because much of the coast is less developed. Water supplies in the region are tight and at greater risk than in the Southeast because the region is more arid and uses a relatively large share of surface and groundwater supplies. Agriculture in the region could decline because of loss of competitiveness to more northern agricultural areas combined with farming in already marginal areas. The risk of disease outbreak may be relatively high along the Rio Grande because of its proximity to Mexico (which has high incidences of disease such as dengue) and the relatively low income of many of its inhabitants. The risk of heat stress is lower than in Northern areas, but slightly higher than in Southeastern cities because temperature variability is slightly higher in this region.

E. Southwest

The Southwest has quite different vulnerabilities to climate change than the rest of the country. It is the most vulnerable region in terms of water supplies (Hurd et al., 1999) because of the combination of a semi-arid to arid climate and relatively high withdrawals of water resources. Earlier snowmelt could increase the risk of winter flooding and summer shortage of water supplies, thereby exacerbating current water scarcities. Should there be increased average annual runoff, some supply concerns may be alleviated, but flooding could increase. Agriculture in the region is projected by economic models to fare relatively well.[10] However, with approximately 90 percent of the region's water consumption going to agriculture, a reduction in water supplies could have a substantial negative effect on that sector. Biodiversity in the region is likely to be reduced because of the complex topography and human development (e.g., dams blocking migration of fish). Yet mountains such as the Rocky Mountains and Sierras also provide north-south and altitudinal migration corridors for some species. Interestingly, species in the Southwest (and Northwest) may not always migrate toward the north because of complex terrain and substantial variances in climate across these regions. Vegetation biomass could increase or decrease, depending on whether the Southwest becomes wetter or drier. There is generally less risk to coastal areas in California than in the Northeast, Southeast, or Southern Great Plains. Nonetheless, San Francisco Bay, the Sacramento-San Joaquin Delta, and many parts of southern California are at risk from sea-level rise. Risks to human health are relatively low because heat stress is not a significant risk in urban areas and there is limited risk of infectious disease outbreaks (although infectious diseases such as hantavirus are a problem in the region). The region's ski industry is likely to be harmed, although warm weather recreation activities could expand.

F. Northwest

It can be argued that the Northwest's relatively cool climate and wet conditions (at least in the western portions of Washington and Oregon) make the region less vulnerable to climate change than warmer or drier regions, yet the region has some distinct vulnerabilities. Changes in the seasonality of runoff could be problematic for management of the region's water resources infrastructure (Hamlet and Lettenmaier, 1999). Much of the coast is not vulnerable to sea-level rise, with the notable exception of the highly developed Puget Sound area. Agricultural production is estimated to increase in the region (Adams et al., 1999a), and ranching could benefit if grassland productivity increases. The effects of climate on forests in the region are uncertain. Under some scenarios, productivity increases, while under others it decreases. Higher temperatures may benefit forests in the region only up to a point, and then they may become a detriment (Neilson and Drapek, 1998). As in the other regions, biodiversity is expected to be harmed, although vegetation productivity could increase. The valuable salmon fishery may be at particular risk from rising temperatures and changes in runoff patterns.

VII. Synthesis of Regional Impacts

On the whole, the Southeast, Southern Great Plains, and Southwest are at greater risk to climate change than other regions. Figure 3 summarizes the impacts on individual sectors in the six regions. Climate change could have negative impacts on many sectors in the three Southern regions, and does not appear to have any positive effects in any sector. In the other three regions, climate change could have mixed effects, harming some sectors and benefiting others.[11] However, one interesting observation is that each region has a sector in which it may be more vulnerable than other regions. The Northeast and Midwest are at greatest risk from increased heat stress. The Southwest has a greater risk to its water supplies, and the Northwest has valuable fisheries that may be at significant risk from climate change.

Figure 3

Regional Impacts by Sector and Region

	Sector							
Region	**Agriculture**	**Water**	**Coastal Communities**	**Health**	**Terrestrial Ecosystem Productivity**	**Terrestrial Biodiversity**	**Forestry**	**Aquatic Biodiversity[12]**
Northeast	⇓ Low	?	⇓ High	⇔ Med	⇑ Low-Med	⇓ Med	⇑ Low	⇔ Low-Med
Southeast	⇓ Med	⇓ Low	⇓ High	⇔ Med	⇔ Low	⇓ Med	⇔ Low	⇓ Med
Southern Great Plains	⇓ Med	⇓ Low	⇓ High	⇔ Med	⇔ Low	⇓ Med	⇔ Low	⇓ Med
Midwest	⇑ Med	⇓ Low	N/A	⇔ Med	⇑ Low-Med	⇓ Med	⇑ Low	⇔ Low-Med
Southwest	⇔ Med	⇓ Low	⇓ High	⇔ Med	⇔ Low	⇓ Med	?	⇓ Med
Northwest	⇑ Med	⇔ Low	⇓ High	⇔ Med	⇔ Low	⇓ Med	?	⇓ Low-Med

Notes: ⇑ indicates positive effects such as increased productivity

⇓ indicates negative effects such as net damages or reduced productivity

⇔ indicates mixed effects, i.e., positive and negative

? indicates uncertainty about the direction of change

The size of the arrow is related to the magnitude of the effect

Low, medium, and high are the levels of confidence in the direction of change

VIII. Damage Estimates for the United States

Some researchers express the impacts of climate change in dollars to estimate the total economic effects of climate change. These studies look at the economic costs of climate change, from infrastructure costs for protecting developed coastal areas to nonmonetary costs such as willingness to pay to avoid adverse impacts on natural ecosystems. The studies provide insight into how total economic impacts may be affected by changes in climate variables such as mean temperature. These studies are reviewed here not so much to emphasize specific results as to assess where they agree and disagree and whether the estimated direction and magnitude of damages have changed over the last decade.

Although these studies express impacts in monetary terms and as a percentage of gross domestic product (GDP), not all impacts have a direct effect on income. Some, such as changes in agricultural production or costs of protecting coastal areas, are direct monetary impacts. These are referred to as "market impacts" because they directly affect goods traded in economic markets. Others affect quality of life, but may not directly affect income. These "nonmarket impacts" include human health, ecosystems, and environmental quality. While there are some direct monetary impacts such as loss of income resulting from injury or death or loss of economic uses of ecosystems, many of the services provided by the affected sectors are not traded in markets. The value of an individual's life is more than what he or she earns, and the value of an endangered species is more than what it may be worth in a market. The value of these goods and services can be estimated in economic terms using techniques such as observed behavioral changes or even expressions of "willingness to pay" for such goods and services (Freeman, 2003).

Before addressing these studies, it is important to understand their limitations (Rothman, 2000). The limitations of total monetary damage estimates include:

- ***Broad use of expert judgment.*** While the total damage studies apply or extrapolate from published estimates of climate change to arrive at national damage estimates, in all but one case, they use expert judgment to estimate monetary consequences of climate change in a number of sectors. For example, they assume levels of migration of people from developing to developed countries, although no detailed study has been conducted on this issue (see Fankhauser, 1995). Such estimates are educated guesses without the benefit of quantitative studies. The exception to this is a study by Mendelsohn and Neumann (1999), updated by Mendelsohn (2001), which based its estimates of damages on empirical studies of sectors, but examined only market sectors.

- ***Monetization of nonmarket impacts.*** In these studies, a significant portion of estimated total damages for the United States comes from so-called nonmarket impacts. These are impacts in sectors for which goods are not normally bought and sold. This includes such impacts as change in quality of life or amenity, mortality, and loss of wetlands and biodiversity. The studies used estimates of people's willingness to pay to obtain services from these sectors or protect them from harm. In many of these studies, the share of damages contributed by such nonmarket impacts is large. There is substantial uncertainty about estimating willingness to pay and controversy about application of economic techniques to derive dollar values for nonmarket impacts. In addition, there have been very few nonmarket valuation studies of climate change impacts. Thus, the magnitude of these effects is highly uncertain.

- ***Development of single estimates of damages.*** All the total damage studies estimate a single level of damages for each climate change scenario or magnitude of change in average temperature. Yet, for any change in average temperature, there is uncertainty about changes in precipitation, regional temperatures, extreme events, and other factors. Even for a given scenario, there are still uncertainties about the direction and magnitude of many impacts. In addition, the range of damages or confidence levels have usually not been estimated (see Rothman, 2000).

- ***Substitution.*** By expressing all impacts in monetary terms, an assumption is implicitly made that one impact can be substituted for another. If loss of life results in $1 billion in damages, but agriculture gains $1 billion, the assumption is made that society is indifferent about the effects of climate change because the net result is $0. However, people may not see such impacts as substitutable.

- ***Assessment only of average and gradual changes.*** The studies do not generally assess the consequences and value of changes in frequency or intensity of extreme events or rapid or nonlinear changes in climate. Should frequency or intensity change, impacts could be substantially or even dramatically more negative than the literature indicates.

- ***Estimation of risk avoidance.*** The studies for the most part do not assess the general preference of people to avoid change. People are often averse to change, particularly change that is uncertain and could have many negative consequences (e.g., Kahneman et al., 1991). Presumably, people would be willing to pay some amount of money to avoid climate change. Nordhaus and Boyer (2000) include a willingness to pay to avoid catastrophe.[13]

Table 1 displays estimated sectoral and total damages for a 2.5°C (4.5°F) warming and 7 percent increase in precipitation from two of the most recent studies on potential monetary damages to the United States.[14] The estimates were adjusted to reflect changes in U.S. GDP.[15] The studies' authors use estimated impacts by other authors and their own judgment to derive damages. In contrast, Mendelsohn (2001) is based on empirical studies of monetary impacts to sectors of the U.S. economy. That study examined the potential for adaptation, particularly driven by market principles (i.e., maximizing economic efficiency), to reduce costs or create benefits. The study does not include many nonmarket impacts, which could, on their own, result in damages. These estimates of damages do not yield consistent results with regard to either total damages or damages to individual sectors. Mendelsohn (2001) estimates net annual benefits of less than $10 billion, and Nordhaus and Boyer (2000) estimate net annual damages to the United States of $21 billion. To put these numbers in perspective, about one-eighth of the U.S. economy, or about $120 billion per year, is in sectors that are relatively sensitive to climate (U.S. BEA, 2002a, 2002b).[16]

Interestingly, there is even more disparity in the results when looking at specific sectors or categories of impacts. Nordhaus and Boyer (2000) estimate net damages of $13 billion to market sectors with a 2.5°C (4.5°F) warming, while Mendelsohn and Neumann (1999) estimate net benefits of $10 billion.

Nordhaus and Boyer's (2000) estimates of market damages are overwhelmed by their estimates of changes in recreation and willingness to pay to avoid extreme and catastrophic events such as collapse of the thermohaline circulation. The benefits to recreation are estimated to be $29 billion, while the willingness to pay to avoid extreme and catastrophic events is estimated to be more than $35 billion; each estimate is about two to three times the total value of impacts to market sectors. There are also substantial differences between the studies' estimated damages to individual sectors such as agriculture and coastal resources.

Table 1

Estimated **Annual Market Impacts** of Climate Change on the U.S. Economy

Study	Nordhaus and Boyer (2000)	Mendelsohn (2001)
Market Impacts:		
Agriculture	–4.85	9.58
Timber	0.00	4.28
Water Resources	0.00	–1.15
Energy	0.00	–2.56
Coastal Structures	–8.47	–0.07
Commercial Fishing	—	—
Total Market (billions 1997$)	**–13.32**	**10.08**
Total Market (% 1997 GDP)[d]	**–0.16%**	**0.12%**
Nonmarket Impacts:		
Water Quality	–1.41	-8.05[c]
Recreation	29.00	7.16[c]
Extreme & Catastrophic Events	–35.30	—
Total Nonmarket (billions 1997$)	**–7.71**	**–0.88[c]**
Total Nonmarket (% 1997 GDP)	**–0.09%**	**0.01%**
Total Market and Nonmarket (billions 1997$)	**–21.03**	**9.20a**
Total Market and Nonmarket (% 1997 GDP)	**0.25%**	**0.10%**

Sectoral impact on the 1997 U.S. economy (billions of 1997$), based on predicted impacts in Nordhaus and Boyer (2000)[a] and Mendelsohn (2001).[b] Missing values indicate that impacts on that sector were not reported in the study. Negative numbers indicate damages, positive numbers indicate benefits. All impacts are in response to a 2.5°C increase in temperature and a 7 percent increase in precipitation.

a Nordhaus and Boyer (2000) based their estimates on a survey of the literature and used expert judgement to derive estimates for a number of sectors that the literature had not covered.

b Mendelsohn (2001) used a combination of cross-sectional studies and spatial equilibrium studies examining potential impacts of climate change. Such studies tend to make optimistic assumptions about adaptation, such as practices in one region can be readily exported to others.

c Values taken from Mendelsohn and Neumann (1999), because only damages to market sectors were reestimated by Mendelsohn (2001).

d Jorgenson et al. (2004) estimate that total market sector impacts for a 3°C warming for the United States are –1.2 percent of U.S. GDP in their "pessimistic" case and +0.7 percent of GDP in their "optimistic" case. The optimistic case is closer to the data used by Nordhaus and Boyer (2000) and by Mendelsohn (2001).

It is interesting to examine how estimates of damages have changed since the early 1990s. Table 2 displays damages to the United States for a 2.5-4°C (4.5-7°F) global average warming cited in the Second Assessment Report of the Intergovernmental Panel on Climate Change (Pearce et al., 1996) and adjusted here to reflect 1997 GDP (thus the absolute numbers are larger than those reported in Pearce et al., 1996).

Figure 4 displays the total damages for Nordhaus and Boyer (2000) and Mendelsohn (2001) resulting from various changes in average temperature (assuming a constant 7 percent increase in precipitation by Mendelsohn and Neumann (1999) for all regions and seasons). Both studies estimate that benefits decline and damages increase at higher temperatures. Nordhaus and Boyer (2000) estimate that

Table 2

Estimated **Annual Market Damages** of Climate Change to the U.S. Economy

Study	Cline (1992)	Fankhauser (1995)	Nordhaus (1991)	Titus (1992)	Tol (1995)
Climate Change Scenario	**+2.5°C**	**+2.5°C**	**+3°C**	**+4°C**	**+2.5°C**
Agriculture	21.2	10.2	1.3	1.5	12.1
Forest Loss	4.7	1.0	—	61.6	—
Species Loss	5.6	11.9	—	—	7.1
Sea-level Rise	9.9	12.7	17.2	8.0	12.0
Electricity	15.2	10.7	1.5	7.6	—
Non-electric Heating	–1.8	—	—	—	—
Total—Market	**54.8**	**46.5**	**20.1**	**78.7**	**31.2**
Human Amenity	—	—	—	—	16.9
Human Life	8.2	16.1	0.0	13.3	52.8
Migration	0.7	0.8	0.0	—	1.4
Hurricanes	1.1	0.3	0.0	—	0.4
Leisure Activities	2.9	—	—	—	—
Availability	9.9	22.0	0.0	16.1	—
Pollution	—	—	—	32.6	—
Urban Infrastructure	0.1	—	—	—	—
Tropical Ozone	4.9	10.3	0.0	38.4	—
Mobile Air Conditioning	—	—	—	2.5	—
Total—Nonmarket[b]	**27.9**	**49.6**	**60.8**	**102.9**	**71.6**
Total—All Sectors	**82.7**	**96.0**	**80.9**	**181.6**	**102.8**
% of GDP (reported)	1.10%	1.30%	1.00%	2.50%	1.50%
% of GDP (actual)	1.02%	1.18%	1.00%	2.24%	1.27%

Annual damages to 1997 U.S. economy (billions of 1997$).[a] Missing values indicate damages to that sector were not assessed for the given study. Positive numbers indicate economic damages.

a Scheraga et al. (1993) used a macroeconomic model of the U.S. economy with assumptions about financial impacts to agriculture, energy, and coastal sectors from climate change. They estimated that GDP would decline by 0.8 percent by 2050.

b Nordhaus (1991) reported nonmarket damages as a percentage of total GDP. The number here was calculated based on the percentage he gave (0.75 percent) of 1990 GDP.

Source: Adapted from Pearce et al. (1996); values adjusted to 1997 GDP.

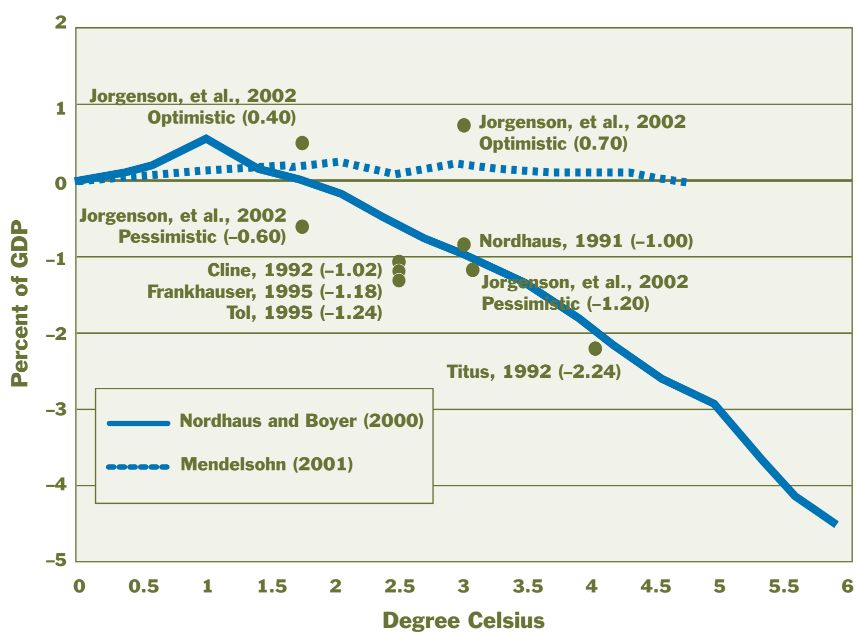
there will be net damages for a warming of about 2°C (4°F), while Mendelsohn (2001) estimates that there will be net damages as temperatures exceed 4°C (7°F). Figure 4 also shows the damages estimated by earlier studies (Nordhaus, 1991; Cline, 1992; Titus, 1992; Frankhauser, 1995; Tol, 1995).

What is striking is that the more recent literature tends to estimate a change in the direction and magnitude of damages. All of the earlier studies estimated net damages of approximately $81 to $182 billion. The more recent studies estimate net benefits for a warming of approximately 1-4°C (2-7°F). Also, the more recent studies estimate net economic impacts of less than $25 billion per year, approximately one-third to one-ninth of earlier estimates.

There are many reasons why the more recent studies tend to estimate lower damages or even benefits at small levels of temperature increase, but chief among them are more optimistic assumptions about the potential for adaptation to offset negative biophysical impacts of climate change and, for vegetation and forestry, inclusion of carbon fertilization in the estimation of biophysical impacts. This is generally true for the studies in Mendelsohn and Neumann (1999), but is also true for other studies such as Darwin et al. (1995) on agriculture, Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) Participants (1995) on terrestrial vegetation, and Perez-Garcia et al. (1997) on forestry.

Figure 4

Estimated **Aggregate Monetary Impacts** of Climate Change on the United States



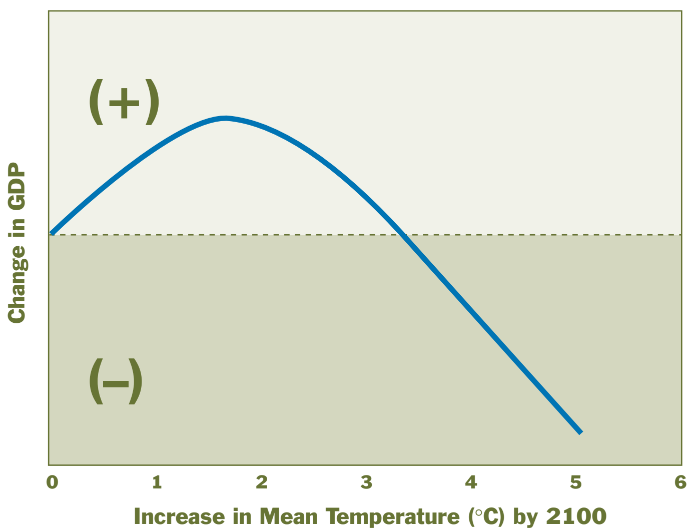
The above figure summarizes the results of several assessments of the impacts of climate change on the U.S. economy. Most of the studies estimate economic impacts for a specific magnitude of future warming. However, two studies [Nordhaus and Boyer (2000) and Mendelsohn (2001)] provide transient estimates reflecting how impacts change over a range of temperature increases. All impacts are in U.S. dollars (1997) as a percentage of gross domestic product (GDP).

On the other hand, it is interesting that most of the studies show that benefits do not keep growing, but at some point start declining and eventually become damages. The studies estimate that economic benefits reach their maximum at about 1-2°C (2-4°F). After that, the level of benefits decline and, beyond approximately 2-4°C (4-7°F), they become damages. This is illustrated by the stylized damage curve in Figure 5. Damages peak between 1°C and 2°C and begin falling after that. Beyond this peak in benefits, additional warming results in marginal losses because the benefits gained from low magnitudes of warming are reduced. With further warming, there are net damages, which continue to grow. This is consistent with the literature, which tends to show greater potential for damages at higher temperatures and at higher concentrations of CO_2. It is also interesting that there is a significant disparity in estimates of damages. For example, Mendelsohn (2001) estimates relatively small economic damages, while Nordhaus and Boyer (2000) estimate much more significant economic damages, particularly beyond a few degrees Celsius of warming.

Figure 5

Threshold for U.S. Economic Impacts

of Climate Change



Stylized damage curve for the estimated impacts of climate change on the U.S. economy. Initially, low magnitudes of warming are estimated to generate net economic benefits, but these benefits peak between approximately 1 and 2°C (2-4°F) of warming. Beyond this point, benefits decline and eventually become damages between approximately 3 and 4°C (5-7°F). The points where benefits peak and net damages occur are consistent with the current literature (see Figure 4), but remain highly uncertain, and thus could be higher or lower.

Finally, Figure 4 also displays results from Jorgenson et al. (2004), who examined the potential magnitude of economic impacts of climate change for a 1.7°C (3.1°F) and 3°C (5.4°F) warming. Their estimate, based on a survey of literature that divided studies into “optimistic” (i.e., relatively more beneficial and generally more recent studies) and “pessimistic” outcomes (i.e., relatively more damaging and generally older studies), is an attempt to estimate the sensitivity of the U.S. economy to climate change rather than develop a best estimate of damages. The Jorgenson et al. (2004) study focused mainly on market sector impacts.[17] It accounts for economic effects across the economy (e.g., an increase in agricultural prices means consumers buy less of other goods, which has additional economic effects). Generally, the magnitude of either pessimistic or optimistic economic impacts estimated in the Jorgenson et al. (2004) study is consistent with the published literature.

It is important to keep in mind the limitations in the economic impacts literature. Not only is there significant uncertainty about how climate will change, but the estimates of climate change impacts do not generally consider such important factors as changes in climate variability and tend to make simple assumptions about such important factors as adaptation and societal development. Thus the specific results should be interpreted with caution. Nonetheless, the more general conclusions about the relative vulnerability of sectors and regions as well as the tendency for there to be damages at higher magnitudes of CO_2 concentrations and temperature increases appear to be robust.

IX. Conclusions

In spite of the uncertainties about climate change, we can, based on the Pew Center on Global Climate Change report series and other literature, draw some conclusions about the relative vulnerability of sectors and regions. As noted above, we are unable to predict the exact effects of climate change, but we are improving our understanding of the sensitivity of various sectors to climate change. Thus, these conclusions should be treated as preliminary.

1) Natural ecosystems appear to be quite vulnerable to climate change. Many natural resources are currently under stress, and climate change could impose additional stress. Climate change threatens to result in the loss of many coral reefs, coastal wetlands, endangered species (particularly those with limited range and mobility), cool- and cold-water fish, boreal species, and alpine species. This threat to natural ecosystems is distinctly more severe because development has reduced species populations, fragmented ecosystems and placed them under stress from pollution, and introduced barriers to migration, such as communities, farms, roads, and dams.

2) A number of sectors in the United States have a high sensitivity to climate change. Climate change could inundate many low-lying coastal areas, put urban areas at risk from increased storms and hurricanes, substantially change runoff in many basins, significantly change crop yields, and result in large geographic shifts and changes in the productivity of terrestrial and aquatic species.

3) The capacity of the U.S. economy as a whole to adapt to a limited amount of climate change, with generally small impacts, appears to be quite high. The country's high per capita income, relatively low population density, research base, institutions, and health care system give the United States a strong capacity to adapt to climate change. There will be costs for adaptation, but relative to the U.S. economy, these costs appear to be small and can most likely be absorbed. Finally, the country's large size and the population's mobility give it advantages in adapting to climate change.

4) Although the nation as a whole has a high capacity to adapt, sectors differ in their vulnerability. Sectors that can change the fastest, such as agriculture, are likely to be best able to adapt to climate change. Sectors with long-lived infrastructure and investments, such as water resources and coastal resources, may have more difficulty adapting and could experience some adverse impacts. However, their ability to adapt to climate change in the long run appears to be high. In contrast, natural ecosystems have a much more limited capacity to adapt to climate change compared to societal sectors.

5) The southern United States is, on the whole, more vulnerable to climate change than the northern United States. Regions such as the Southeast and Southern Great Plains appear to be more vulnerable to climate change than the nation as a whole. In some regions, specific sectors, such as water resources in the Southwest, are at particular risk from climate change.

6) Even within regions that may have net economic benefits, individual communities and people could be adversely affected. Those with limited financial resources and mobility may be at greatest risk to climate change. The urban poor appear to have the highest risk from increased heat stress. Poor farmers may be most vulnerable to changes in agricultural conditions. Poor and isolated populations, such as Native Americans, may be at risk should climate change substantially affect the natural resources on which they depend.

7) Studies of the economic impacts of climate change indicate that impacts for a few degrees of warming will be less than ±1 percent of gross domestic product (GDP). These studies tend to incorporate both market and nonmarket (e.g., biodiversity and quality of life) impacts and, as noted above, assume a gradual change in climate and no change in variability. Economic studies based on impact assessments conducted during the late 1980s and early 1990s tend to show damages of about 1 percent of GDP. More recent studies that consider new findings on the biophysical impacts of climate change and fully account for the potential for adaptation yield different results. These economic studies suggest that for up to 2-4°C (4-7°F) of warming, there could be net economic benefits of less than 1 percent of GDP. It is possible that because of factors not considered, economic impacts could be more negative than these studies estimate.

8) Economic impacts studies indicate that while there could be benefits from climate change, which peak at a few degrees of warming, there would be damages at higher levels of warming. Economic studies indicate that even in those sectors, such as agriculture, estimated to benefit from a small magnitude of warming, these benefits peak and subsequently decline. This is because beyond certain increases in temperatures, crop yields decline or the "carbon fertilization" effect, which enables plants to grow more and use less water, saturates at higher CO_2 concentrations. In addition, other transient benefits such as reduced energy demand eventually become reversed as costs for cooling rise and savings from less heating are reduced. This is even true for regions such as the northern United States, which may experience economic benefits from a warming of less than several degrees, but losses beyond that. Economic studies suggest that benefits peak at approximately a 1-2°C (2-4°F) increase in mean temperature. Beyond this, benefits decline until net economic damages occur at a warming of approximately 2-4°C (4-7°F) and become progressively worse with further increases in temperature. Significant uncertainty exists about the level of increased temperature that leads to damages and the magnitude of damages beyond that point.

9) The rate and path of climate change matter. A gradual and monotonic change in climate (e.g., steady increases or decreases in precipitation) will be much easier to adapt to than rapid changes in climate or increased interannual or interdecadal climate variability. In a slowly and steadily changing climate, such adaptations as replacing infrastructure and introducing new technologies can be made gradually. A more rapid change in climate may necessitate more rapid than normal investments in infrastructure, technology, and other adaptations. These investments could be costly.

10) Increased warming heightens the risk of triggering large-scale changes to the climate system. Substantial increases in global mean temperature could set off large-scale changes to the earth's system such as shutdown of the thermohaline circulation (i.e., the Gulf Stream) or melting of the West Antarctic ice sheet. The thresholds are uncertain (and for some of these events may be quite high), the time frames of the consequences of such events may take centuries to be fully realized, and the consequences are not currently well understood. However, it is possible that warming in the 21st century could trigger such events. Once started, they may be extremely difficult, if not impossible, to reverse.

Endnotes

1. Vulnerability is determined by the exposure of a system to climate change (i.e., how much the regional climate changes), the sensitivity of the system to the change (how much changing temperatures can affect the system), and the ability of the system to adapt to the changes. If a system can adapt and maintain the services it provided before climate change, it has low vulnerability. In contrast, if a system has a limited capacity to adapt and is likely to be adversely affected by climate change, it has high vulnerability.

2. While the observational record indicates that precipitation and precipitation intensity have increased (Karl and Knight, 1998), Vinnikov and Robock (2002) found no observable change in precipitation variability in the United States in the 20th century. They did not examine temperature.

3. Schneider et al. (2000a) explore the effect of a delayed adaptation response by farmers on crop yields. They find that impacts are less positive than when instant and perfect foresight about climate change is assumed, but more positive than when no adaptation is assumed. This suggests that assumptions about adaptation are a critical factor in determining the sign and magnitude of damages. Predictions of vulnerability would be improved by a better understanding of how adaptation will happen.

4. For example, Changnon et al. (1989) note that when levels of the Great Lakes fell in the early 1960s, development moved closer to the receding shoreline. When lake levels rose in the early 1980s, some of that development was damaged.

5. Mendelsohn and Markowski (1999) and Loomis and Crespi (1999) estimated potential changes in recreation. This is a difficult topic to study and the results should be treated as preliminary. Yet, this is potentially an important economic impact, which should be the subject of more research.

6. The importance of this topic has received more attention recently, e.g., National Research Council (2002) and Schneider et al. (2000b).

7. Analysis for the U.S. National Assessment found that there is potential for increased national agricultural output, although production is estimated to decline in the 2030s under one scenario. Adaptation can substantially mitigate this loss (NAST, 2000).

8. Frederick and Schwarz (1999) examined the infrastructure costs and lost services associated with responding to increased drought risk from the Canadian and Hadley scenarios used in the U.S. National Assessment (Felzer and Heard, 1999) using change in runoff estimated by Wolock and McCabe (1999, cited in Frederick and Gleick, 1999). The Canadian scenario results in estimates of extreme reductions in runoff in 2030 in three basins: the South Atlantic-Gulf, Texas-Gulf, and Rio Grande. Frederick and Schwarz estimate that annual infrastructure costs and residual damages from responding to the Canadian scenario would be $105 billion in 2030. However, under the Hadley scenario, they estimate that expenditures would decrease by $5 billion. To put these numbers in perspective, in 1996 the United States invested $28 billion in water supply infrastructure (U.S. Statistical Abstract, 1999). The estimates do not consider increased costs of protection from flooding or, where appropriate, benefits of reduced flooding. The extreme nature of the estimated runoff under the Canadian scenario implies that these results should be treated with caution. It is not known if the 2030s results reflect climate variability in the Canadian model rather than climate change. Nonetheless, the results demonstrate the high sensitivity of the water resources sector to climate.

9. Martens (1998) estimates that cold weather mortality in northern cities could decrease, but he did not examine increased mortality resulting from heat waves. Thus, it is not known whether decreased winter mortality would offset increased mortality from heat stress.

10. One problem in determining how agriculture in the Southwest may be affected by climate change is that one of the major models used to assess impacts of climate change on agriculture, the Agriculture Simulation Model (Adams et al., 1999b), follows the U.S. Department of Agriculture regions, which assigns the southwestern states to a "West" region consisting of the Pacific coast states and a "Mountain" region consisting of the Rocky Mountain states. It is possible that the estimated increases in production in the West and Mountain regions may be mainly or only taking place in the northern and coastal parts of those regions.

11. Saying that a region or nation might have mixed effects does not imply that negative and positive impacts cancel out. This section of the report does not address the relative value or importance of impacts across sectors.

12. The estimation of regional impacts considers only the impacts on freshwater and estuaries. There is too much uncertainty about open ocean impacts to differentiate among regions in the United States.

13. Nordhaus and Boyer (2000) assume that Europeans have a much greater willingness to pay to avoid catastrophe than do North Americans. It could be argued that willingness-to-accept (WTA) compensation may be a more appropriate measure of damages, particularly for those who may have climate change impacts imposed on them. WTA levels tend to be significantly higher than willingness-to-pay levels (Kahneman et al., 1991).

14. Tol (1999) also estimates aggregate damages for the United States, but for a 1°C warming. He reports that total benefits to the United States would be $190 billion (in $1997 and based on 1997 GDP), or 3.2 percent of GDP. However, Tol does not report benefits for all sectors. This makes it difficult to reconstruct how he arrived at his estimate of total damages, so his results are not further analyzed in this report.

15. The published damage estimates were adjusted to 1997 conditions based on changes in sectoral GDP for agriculture, timber, and energy and based on total GDP for all other sectors (U.S. BEA, 2002b). The assumption is that the percentage change in each sector stays the same, and that the value of coastal structures, ecosystems, water quality, and recreation would increase commensurate with total GDP.

16. This estimate includes sectors that are clearly sensitive to climate, such as agriculture and forestry, but it also includes construction and tourism. As noted in the text, tourism is 6.5 percent of GDP (based on direct and indirect tourism related sales). Agriculture (including fishing, forestry, and agricultural services) is 1.4 percent of the economy, while construction is 4.7 percent (U.S. BEA, 2002b). This figure is not necessarily an upper bound for what sectors of the economy are sensitive to climate because extreme climate can affect many parts of the economy by affecting such critical services as transportation and water supply.

17. Jorgenson et al. (2004) also included an analysis of impacts of climate change on human welfare. The magnitude of these impacts is quite significant.

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notes

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