CLIMATE CHANGE IMPACTS ON THE UNITED STATES

The Potential Consequences of Climate Variability and Change

Foundation

Humanity's influence on the global climate will grow in the 21st century. Increasingly, there will be significant climate-related changes that will affect each one of us.

We must begin now to consider our responses, as the actions taken today will affect the quality of life for us and future generations.

A Report of the National Assessment Synthesis Team

US Global Change Research Program

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Comments on this report should be addressed to:
Office of the US Global Change Research Program
400 Virginia Avenue SW, Suite 750, Washington DC 20024
http://www.usgcrp.gov

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FOREWORD

The National Assessment of the Potential Consequences of Climate Variability and Change is a landmark in the major ongoing effort to understand what climate change means for the United States. Climate science is developing rapidly and scientists are increasingly able to project some changes at the regional scale, identifying regional vulnerabilities, and assessing potential regional impacts. Science increasingly indicates that the Earth's climate has changed in the past and continues to change, and that even greater climate change is very likely in the 21st century. This Assessment has begun a national process of research, analysis, and dialogue about the coming changes in climate, their impacts, and what Americans can do to adapt to an uncertain and continuously changing climate. This Assessment is built on a solid foundation of science conducted as part of the United States Global Change Research Program (USGCRP).

This document is the Foundation report, which provides the scientific underpinnings for the Assessment. It has been prepared in cooperation with independent regional and sector assessment teams under the leadership of the National Assessment Synthesis Team (NAST). The NAST is a committee of experts drawn from governments, universities, industry, and non-governmental organizations. It has been responsible for preparing an Overview report aimed at general audiences and for broad oversight of the Assessment along with the Federal agencies of the USGCRP. These two national-level, peer-reviewed documents synthesize results from studies conducted by regional and sector teams, and from the broader scientific literature.

This Assessment was called for by a 1990 law, and has been conducted under the authority of the USGCRP in response to a request from the President's Science Advisor. The NAST developed the Assessment's plan, which was then approved by the National Science and Technology Council, the cabinet level body of agencies responsible for scientific research, including global change research, in the US government. We would like to acknowledge their contributions to this effort. The agencies and their representatives are listed in the appendix to this volume. Of particular note have been Rosina Bierbaum and Peter Backlund of the Office of Science and Technology Policy, who provided consistent and helpful guidance throughout, and who organized our Oversight Board. In addition, Robert Corell (now a NAST Member), Aristides Patrinos, Paul Dresler, Richard Ball, Joel Scheraga, and Tom Spence, along with many additional individuals, have played major roles on behalf of the Subcommittee on Global Change Research, its National Assessment Working Group, and the ten cooperating agencies.

These assessment reports could not have been prepared without the extraordinary efforts of a large number of people. In addition to the members of the NAST, a number of individuals were entrained into development of the content and findings of the report, both as lead authors for the Overview and as lead and contributing authors for the chapters in this Foundation report. We want to express our sincere gratitude to these authors, the many names of whom are listed in the Overview report and in the chapter headings of this book. Those playing particularly important roles in the preparation of major sections of the Foundation report included Susan Bernard, Lynne Carter, David Easterling, Benjamin Felzer, John Field, Paul Grabhorn, Susan Jay Hassol, Schuyler Houser, Michael MacCracken, Michael McGeehin, Jonathan Patz, John Reilly, Joel Smith, Melissa Taylor, and Tom Wilbanks.

The report itself is based in large part on workshops and assessment efforts of five sector teams and teams in 20 regions across the US. Each of these groups has in turn involved many more experts from universities, governments at various levels, public and private organizations, and others interested in or affected by the changing global environment. All of these individuals have played an important role in developing and expanding the dialogue on the potential impacts of climate change. We want to especially thank the various regional and sector team leaders who are listed along with their team members in the chapters of this report.

In addition, we benefited from the comments of hundreds of reviewers, who helped encourage new insights and new ways of thinking about and presenting the results of these studies. Of particular help were the members of the Independent Review Board that was established by the President's Committee of Advisers on Science and Technology. Co-chaired by Peter Raven and Mario Molina, the board included Burton Richter, Linda Fisher, Kathryn Fuller, John Gibbons, Marcia McNutt, Sally Ride, William Schlesinger, James Gustave Speth, and Robert White. They provided cogent and helpful comments throughout the many drafts of the assessment documents.

The complexity of coordinating the activities of far-flung authors, providing background data, managing the inputs and responses from hundreds of reviewers, designing the reports to be accurate, accessible, and appealing, and ensuring that the final products were printed under tight timetables was very challenging. Many people devoted their personal and professional attention to those tasks without asking for credit. Here we acknowledge their contributions and dedication to seeing this job through, and thank them, most assuredly less than they deserve. Paul Grabhorn kept us focused on effectively communicating our message, helped us appreciate the importance of design, and he, Melody Warford, and their staff carried this through with an inspired design implemented through layout, graphics, and production of the documents. Susan Joy Hassol, with the gracious cooperation of the Aspen Global Change Institute, played a major role in making complex scientific issues more easily understood and helping our convoluted prose speak more clearly.

The staff of the National Assessment Coordination Office (NACO) played an important role in facilitating the entire assessment process by supporting the activities not only of the NAST, but also by coordinating the efforts of the regions, sectors, and agencies. Under the leadership of Michael MacCracken, the coordination and logistics associated with this very distributed effort came together. Melissa Taylor served as executive secretary to the NAST through March 2000. Lynne Carter served as NACO liaison to the regions, Justin Wettstein and LaShaunda Malone served as liaison to the sectors, and LaShaunda Malone also served as liaison with agencies and as coordinator for the various peer reviews. Thomas Wilbanks of Oak Ridge National Laboratory (ORNL) served as chair of the Inter-regional Forum that helped to encourage and coordinate regional activities. In addition, Forrest Hoffman of ORNL handled the Web site through which much of our information was distributed. The NACO staff were also assisted in their efforts by staff of the Global Change Research Information Office, including Robert Worrest, Annie Gerard, and Robert Bourdeau, who have helped in the posting of the full report for public comment and access.

The assessment studies are based on extensive data sets of various types. Benjamin Felzer, with assistance of staff at the National Center for Atmospheric Research (NCAR), assembled and analyzed the data from climate models and prepared most of the climate graphics. David Easterling, Byron Gleason, and other staff at the National Climatic Data Center provided databases describing past changes in the climate. Tim Kittel at the National Center for Atmospheric Research was instrumental in carrying through the processing of the climatic data to provide consistent sets for use across the US. We also very much appreciate the willingness of colleagues at the various modeling centers to provide results of their simulations, including particularly David Viner at the University of East Anglia, Francis Zwiers and George Boer at the Canadian Centre for Climate Modelling and Analysis, and John Mitchell, Ruth Carnell, and Jonathan Gregory at the Hadley Centre of the United Kingdom Meteorological Office. The availability of data for the assessment teams was made possible by Ben Felzer of NCAR and Annette Schloss and Denise Blaha of the University of New Hampshire.

Baseline distributions and simulations of changes in ecosystems were made available through the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) and their many team members. Tim Kittel of NCAR graciously served as coordinator of our links to this effort. The social science data sets were provided by Nestor Terlickij of NPA Data Associates through an agreement with the Oak Ridge National Laboratory based on the efforts of David Vogt and Thomas Wilbanks. In addition, Robert Chen at the Consortium for International Earth Science Information Networks (CIESIN) provided very helpful data sets on population and other social measures.

Many individuals have played important roles in carrying through the administrative aspects of this effort. We want to graciously acknowledge the contributions of Mary Ann Seifert of the Marine Biological Laboratory, Gracie Bermudez of the World Resources Institute, Rosalind Ledford of the National Climatic Data Center, Nakia Dawkins and Robert Cherry of NACO, and Susan Henson, Karen York, and Matt Powell of the National Science Foundation, all of whom assisted in making possible our many meetings and exchanges of reports, among many other tasks. In addition, the staff of the University Corporation for Atmospheric Research (UCAR) provided invaluable assistance with travel and contractual issues associated with the assessment process. Those playing particularly helpful efforts have been Gene Martin, Kyle Terran, Tara Jay, Amy Smith, Chrystal Pene, James Menghi, and Brian Jackson.

Finally, as co-chairs of the National Assessment Synthesis Team, we would like to thank the other members of this team. We have had quite an adventure, working to develop and analyze information, working with fellow NAST members and leaders of assessment teams around the country, considering and coming to agreement on findings, and writing and rewriting text in response to internal and external comments. Throughout there has been great comity, and we are very proud to have come to full consensus on all of the findings. We want to thank all of you especially for devoting your time and effort to this important effort; we know it has involved much more than any of you first thought, but we believe the product is also a very significant contribution to the Nation’s future.

Jerry Melillo
Anthony Janetos
Thomas Karl

National Assessment Synthesis Team Members

Jerry M. Melillo, Co-chair
Ecosystems Center
Marine Biological Laboratory

Anthony C. Janetos, Co-chair
World Resources Institute

Thomas R. Karl, Co-chair
NOAA National Climatic Data Center

Eric J. Barron
Pennsylvania State University

Virginia Burkett
USGS National Wetlands Research Center

Thomas F. Cecich
Glaxo Wellcome Inc.

Robert Corell (from January 2000)
American Meteorological Society and
Harvard University

Katharine Jacobs
Arizona Department of Water Resources

Linda Joyce
USDA Forest Service

Barbara Miller
World Bank

M. Granger Morgan
Carnegie Mellon University

Edward A. Parson (until January 2000)
Harvard University

Richard G. Richels
EPRI

David S. Schimel
National Center for Atmospheric Research

Independent Review Board of the President's Committee of Advisers on Science and Technology (PCAST)

Peter Raven, Co-chair
Missouri Botanical Garden and PCAST

Mario Molina, Co-chair
MIT and PCAST

Burton Richter
Stanford University

Linda Fisher
Monsanto

Kathryn Fuller
World Wildlife Fund

John Gibbons
National Academy of Engineering

Marcia McNutt
Monterey Bay Aquarium Research Institute

Sally Ride
University of California San Diego and PCAST

William Schlesinger
Duke University

James Gustave Speth
Yale University

Robert White
University Corporation for Atmospheric
Research, and Washington Advisory Group

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ABOUT THE ASSESSMENT PROCESS

What is the purpose of this Assessment?

The Assessment's purpose is to synthesize, evaluate, and report on what we presently know about the potential consequences of climate variability and change for the US in the 21st century. It has sought to identify key climatic vulnerabilities of particular regions and sectors, in the context of other changes in the nation's environment, resources, and economy. It has also sought to identify potential measures to adapt to climate variability and change. Finally, because present knowledge is limited, the Assessment has sought to identify the highest priority uncertainties about which we must know more to understand climate impacts, vulnerabilities, and our ability to adapt.

How did the process involve both stakeholders and scientists in this Assessment?

This first National Assessment involved both stakeholders and scientific experts. Stakeholders included, for example, public and private decision-makers, resource and environmental managers, and the general public. The stakeholders from different regions and sectors began the Assessment by articulating their concerns in a series of workshops about climate change impacts in the context of the other major issues they face. In the workshops and subsequent consultations, stakeholders identified priority regional and sector concerns, mobilized specialized expertise, identified potential adaptation options, and provided useful information for decision-makers. The Assessment also involved many scientific experts using advanced methods, models, and results. Further, it has stimulated new scientific research in many areas and identified priority needs for further research.

What is the breadth of this Assessment?

Although global change embraces many interrelated issues, this first National Assessment has examined only climate change and variability, with a primary focus on specific regions and sectors. In some cases, regional and sector analyses intersect and complement each other. For example, the Forest sector and the Pacific Northwest have both provided insights into climate impacts on Northwest forests.

The regions cover the nation. Impacts outside the US are considered only briefly, with particular emphasis on potential linkages to the US. Sector teams examined Water, Agriculture, Human Health, Forests, and Coastal Areas and Marine Resources. This first Assessment could not attempt to be comprehensive: the choice of these five sectors reflected an expectation that they were likely to be both important and particularly informative, and that relevant data and analytic tools were available – not a conclusion that they are the only important domains of climate impact. Among the sectors considered, there was a continuum in the amount of information available to support the Assessment, with some sectors being at far earlier stages of development. Future assessments should consider other potentially important issues, such as Energy, Transportation, Urban Areas, and Wildlife.

Each regional and sector team is publishing a separate report of its own analyses, some of which are still continuing. The Overview and Foundation reports consequently represent a snapshot of our understanding at the present time.

After identifying potential impacts of climate change, what kinds of societal responses does this report explore?

Responses to climate change can be of two broad types. One type involves adaptation measures to reduce the harms and risks and maximize the benefits and opportunities of climate change, whatever its cause. The other type involves mitigation measures to reduce human contributions to climate change. After identifying potential impacts, this Assessment sought to identify potential adaptation measures for each region and sector studied. While this was an important first step, it was not possible at this stage to evaluate the practicality, effectiveness, or costs of the potential adaptation measures. Both mitigation and adaptation measures are necessary elements of a coherent and integrated response to climate change. Mitigation measures were not included in this Assessment but are being assessed in other bodies such as the United Nations Intergovernmental Panel on Climate Change (IPCC).

Does the fact that this report excludes mitigation mean that nothing can be done to reduce climate change?

No. An integrated climate policy will combine mitigation and adaptation measures as appropriate. If future world emissions of greenhouse gases are lower than currently projected, for whatever reason, including intentional mitigation, then the rate of climate change, the associated impacts, and the cost and difficulty of adapting will all be reduced. If emissions are higher than expected, then the rate of change, the impacts, and the difficulty of adapting will be increased. But no matter how aggressively emissions are reduced, the world will still experience at least a century of climate change. This will happen because the elevated concentrations of greenhouse gases already in the atmosphere will remain for many decades, and because the climate system responds to changes in human inputs only very slowly. Consequently, even if the world takes mitigation measures, we must still adapt to a changing climate. Similarly, even if we take adaptation measures, future emissions will have to be curbed to stabilize climate. Neither type of response can completely supplant the other.

How are computer models used in this Assessment?

State-of-the-science climate models have been used to generate climate change scenarios. Computer models of ecological systems, hydrological systems, and various socioeconomic systems have also been used in the Assessment to study responses of these systems to the scenarios generated by climate models.

What additional tools, besides models, were used to evaluate potential climate change impacts?

In addition to models, the Assessment has used two other ways to think about potential future climate. First, the Assessment has used historical climate records to evaluate sensitivities of regions and sectors to climate variability and extremes that have occurred in the 20th century. Looking at real historical climate events, their impacts, and how people have adapted, gives valuable insights into potential future impacts that complement those provided by model projections. In addition, the Assessment has used sensitivity analyses, which ask how, and how much, the climate would have to change to bring about major impacts on particular regions or sectors. For example, how much would temperature have to increase in the South before agricultural crops such as soybeans would be negatively affected? What would be the result for forest productivity of continued increases in temperature and leveling off of the CO_2 fertilization effect?

Has this report been peer reviewed?

This Overview and the underlying Foundation document have been extensively reviewed. More than 300 scientific and technical experts have provided detailed comments on part or all of the report in two separate technical reviews. The report was reviewed at each stage for technical accuracy by the agencies of the US Global Change Research Program. The public also provided hundreds of helpful suggestions for clarification and modification during a 60-day public comment period. A panel of distinguished experts convened by the President's Committee of Advisors on Science and Technology has provided broad oversight and monitored the authors response to all reviews.

ABOUT SCENARIOS AND UNCERTAINTY

What are scenarios and why are they used?

Scenarios are plausible alternative futures – each an example of what might happen under particular assumptions. Scenarios are not specific predictions or forecasts. Rather, scenarios provide a starting point for examining questions about an uncertain future and can help us visualize alternative futures in concrete and human terms. The military and industry frequently use these powerful tools for future planning in high-stakes situations. Using scenarios helps to identify vulnerabilities and plan for contingencies.

Many of the maps in this document are derived from the two primary climate model scenarios. In most cases, there are three maps: one shows average conditions based on actual observations from 1961-1990; the other two are generated by the Hadley and Canadian model scenarios and reflect the models' projections of change from present day conditions.

Why are climate scenarios used in this Assessment and how were they developed?

Because we cannot predict many aspects of our nation's future climate, we have used scenarios to help explore US vulnerability to climate change. Results from state-of-the-science climate models and data from historical observations have been used to generate a variety of such scenarios. Projections of changes in climate from the Hadley Centre in the United Kingdom and the Canadian Centre for Climate Modeling and Analysis served as the primary resources for this Assessment. Results were also drawn from models developed at the National Center for Atmospheric Research, NOAA's Geophysical Fluid Dynamics Laboratory, and NASA's Goddard Institute for Space Studies.

For some aspects of climate, virtually all models, as well as other lines of evidence, agree on the types of changes to be expected. For example, all climate models suggest that the climate is going to get warmer, the heat index is going to rise, and precipitation is more likely to come in heavy and extreme events. This consistency lends confidence to these results.

For some other aspects of climate, however, the model results differ. For example, some models, including the Canadian model, project more extensive and frequent drought in the US, while others, including the Hadley model, do not. The Canadian model suggests a drier Southeast in the 21st century while the Hadley model suggests a wetter one. In such cases, the scenarios provide two plausible but different alternatives. Such differences can help identify areas in which the models need improvement.

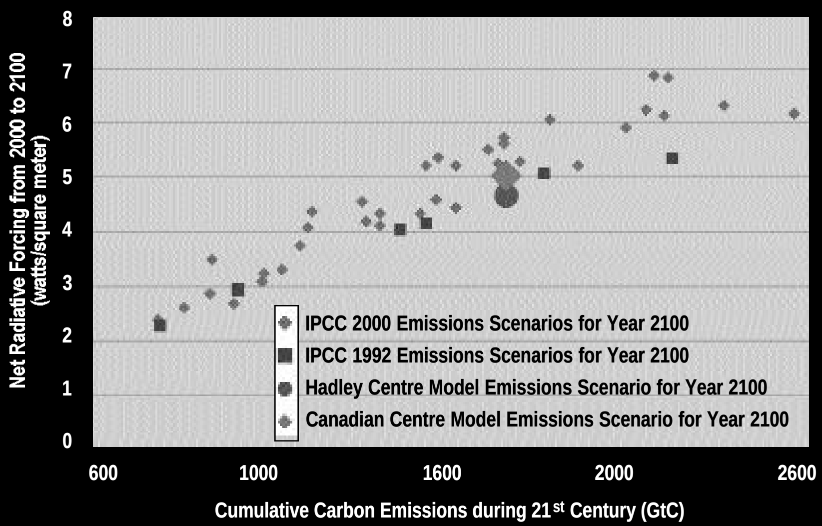
Many of the maps in this document are derived from the two primary climate model scenarios. In most cases, there are three maps: one shows average conditions based on actual observations from 1961-1990; the other two are generated by the Hadley and Canadian model scenarios and reflect the models' projections of change from those average conditions.

What assumptions about emissions are in these two climate scenarios?

Because future trends in fossil fuel use and other human activities are uncertain, the Intergovernmental Panel on Climate Change (IPCC) has developed a set of scenarios for how the 21st century may evolve. These scenarios consider a wide range of possibilities for changes in population, economic growth, technological development, improvements in energy efficiency, and the like. The two primary climate scenarios used in this Assessment are based on one mid-range emissions scenario for the future that assumes no major changes in policies to limit greenhouse gas emissions. Some other important assumptions in this scenario are that by the year 2100:

- **world population will nearly double to about 11 billion people;**
- **the global economy will continue to grow at about the average rate it has been growing, reaching more than ten times its present size;**
- **increased use of fossil fuels will triple CO_2 emissions and raise sulfur dioxide emissions, resulting in an atmospheric CO_2 concentration of just over 700 parts per million; and**
- **total energy produced each year from non-fossil sources such as wind, solar, biomass, hydroelectric, and nuclear will increase to more than ten times its current amount, providing more than 40% of the world's energy, rather than the current 10%.**

The Assessment's Emissions Scenario Falls in the Middle of the other IPCC Emissions Scenarios



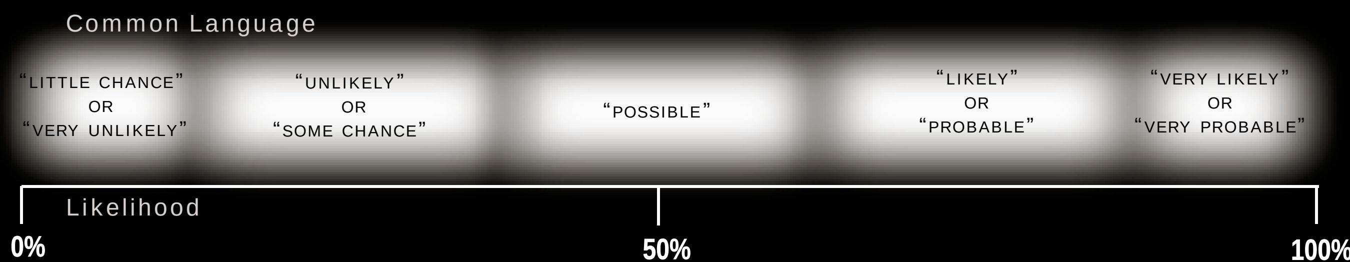
The graph shows a comparison of the projections of total carbon dioxide emissions (in billions of metric tons of carbon, GtC) and the human-induced warming influence due to all the greenhouse gases and sulfate aerosols for the emissions scenarios prepared by the IPCC in 1992 and 2000. As is apparent from the graph, both the emissions scenario and the human-induced warming influence assumed in this Assessment lie near the mid-range of the set of IPCC scenarios. Further detail can be found in the Climate chapter . See color figure section.

Both the emissions scenario and the human-induced warming influence assumed in this Assessment lie near the mid-range of the set of IPCC scenarios.

How is the likelihood of various impacts expressed?

To integrate a wide variety of information and differentiate more likely from less likely outcomes, the NAST developed a common language to express the team's considered judgement about the likelihood of results. The NAST developed their collective judgements through discussion and consideration of the supporting information. Historical data, model projections, published scientific literature, and other available information all provided input to these deliberations, except where specifically stated that the result comes from a particular model scenario. In developing these judgements, there were often several lines of supporting evidence (e.g., drawn from observed trends, analytic studies, model simulations). Many of these judgements were based on broad scientific consensus as stated by well-recognized authorities including the IPCC and the National Research Council. In many cases, groups outside the NAST reviewed the use of terms to provide input from a broader set of experts in a particular field.

Language Used to Express Considered Judgement



SUMMARY

CLIMATE CHANGE AND OUR NATION

The findings in this report are based on a synthesis of historical data, model projections, published scientific research, and other available information, except where specifically noted.

Long-term observations confirm that our climate is now changing at a rapid rate. Over the 20th century, the average annual US temperature has risen by almost 1°F (0.6°C) and precipitation has increased nationally by 5 to 10%, mostly due to increases in heavy downpours. These trends are most apparent over the past few decades. The science indicates that the warming in the 21st century will be significantly greater than in the 20th century. Scenarios examined in this Assessment, which assume no major interventions to reduce continued growth of world greenhouse gas emissions, indicate that temperatures in the US will rise by about 5-9°F (3-5°C) on average in the next 100 years, which is more than the projected *global* increase. This rise is very likely to be associated with more extreme precipitation and faster evaporation of water, leading to greater frequency of both very wet and very dry conditions.

This Assessment reveals a number of national-level impacts of climate variability and change including impacts to natural ecosystems and water resources. Natural ecosystems appear to be the most vulnerable to the harmful effects of climate change, as there is often little that can be done to help them adapt to the projected speed and amount of change. Some ecosystems that are already constrained by climate, such as alpine meadows in the Rocky Mountains, are likely to face extreme stress, and disappear entirely in some places. It is likely that other more widespread ecosystems will also be vulnerable to climate change. One of the climate scenarios used in this Assessment suggests the potential for the forests of the Southeast to break up into a mosaic of forests, savannas, and grasslands. Climate scenarios suggest likely changes in the species composition of the Northeast forests, including the loss of sugar maples. Major alterations to natural ecosystems due to climate change could possibly have negative consequences for our economy, which depends in part on the sustained bounty of our nation's lands, waters, and native plant and animal communities.

A unique contribution of this first US Assessment is that it combines national-scale analysis with an examination of the potential impacts of climate change on different regions of the US. For example, sea-level rise will very likely cause further loss of coastal wetlands (ecosystems that provide vital nurseries and habitats for many fish species) and put coastal communities at greater risk of storm surges, especially in the Southeast. Reduction in snowpack will very likely alter the timing and amount of water supplies, potentially exacerbating water shortages and conflicts, particularly throughout the western US. The melting of glaciers in the high-elevation West and in Alaska represents the loss or diminishment of unique national treasures of the American landscape. Large increases in the heat index (which combines temperature and humidity) and increases in the frequency of heat waves are very likely. These changes will, at minimum, increase discomfort, particularly in cities. It is very probable that continued thawing of permafrost and melting of sea ice in Alaska will further damage forests, buildings, roads, and coastlines, and harm subsistence livelihoods. In various parts of the nation, cold-weather recreation such as skiing will very likely be reduced, and air conditioning usage will very likely increase.

Highly managed ecosystems appear more robust, and some potential benefits have been identified. Crop and forest productivity is likely to increase in some areas for the next few decades due to increased carbon dioxide in the atmosphere and an extended growing season. It is possible that some US food exports could increase,depending on impacts in other food-growing regions around the world. It is also possible that a rise in crop production in fertile areas could cause prices to fall,benefiting consumers. Other benefits that are possible include extended seasons for construction and warm weather recreation, reduced heating requirements,and reduced cold-weather mortality.

Climate variability and change will interact with other environmental stresses and socioeconomic changes. Air and water pollution,habitat fragmentation, wetland loss,coastal erosion,and reductions in fisheries are likely to be compounded by climate-related stresses. An aging populace nationally, and rapidly growing populations in cities,coastal areas,and across the South and West,are social factors that interact with and alter sensitivity to climate variability and change.

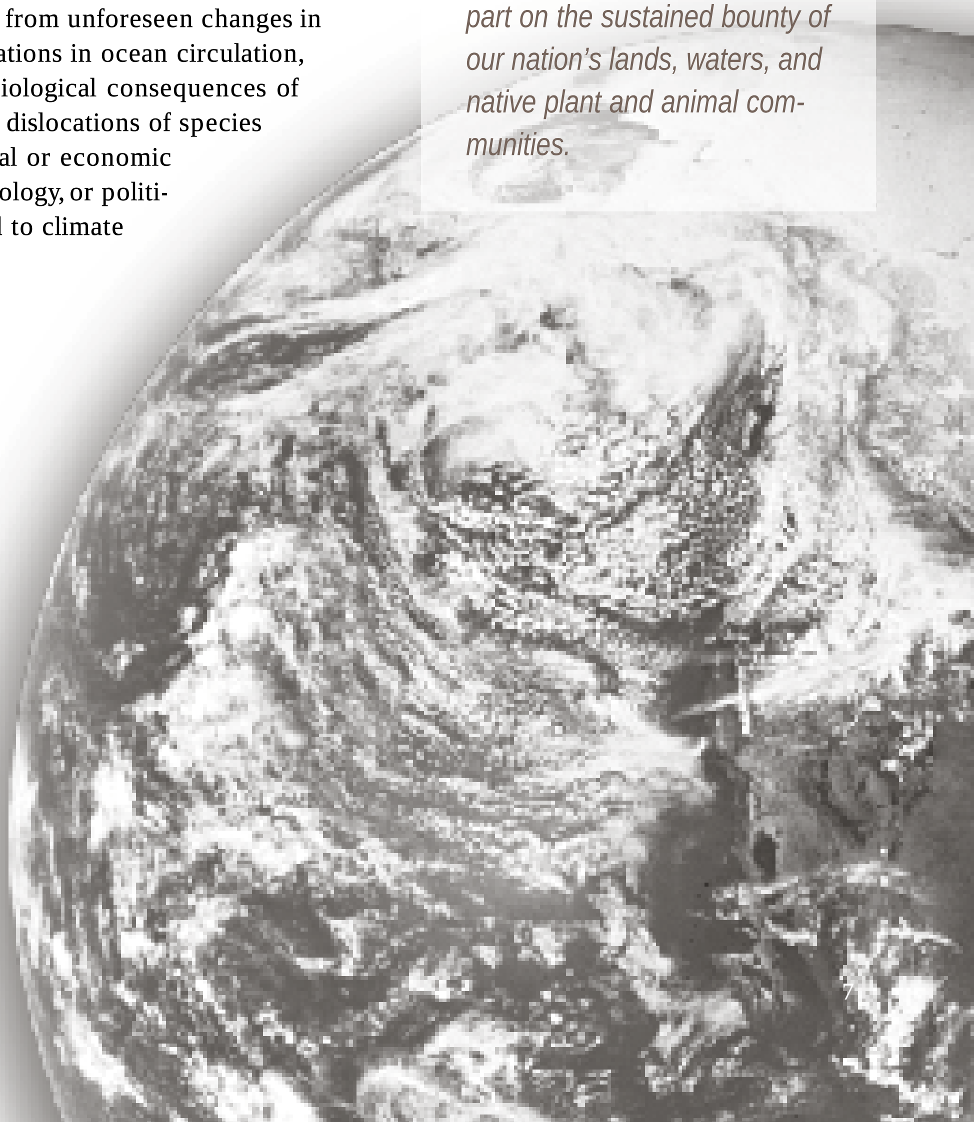
There are also very likely to be unanticipated impacts of climate change during the 21st century. Such "surprises" may stem from unforeseen changes in the physical climate system,such as major alterations in ocean circulation, cloud distribution,or storms;and unpredicted biological consequences of these physical climate changes,such as massive dislocations of species or pest outbreaks. In addition,unexpected social or economic changes,including major shifts in wealth,technology, or political priorities,could affect our ability to respond to climate change.

Greenhouse gas emissions lower than those assumed in this Assessment would result in reduced impacts. The signatory nations of the Framework Convention on Climate Change are negotiating the path they will ultimately take. Even with such reductions,however, the planet and the nation are certain to experience more than a century of climate change,due to the long lifetimes of greenhouse gases already in the atmosphere and the momentum of the climate system. Adapting to a changed climate is consequently a necessary component of our response strategy.

The warming in the 21st century will be significantly greater than in the 20th century.

Natural ecosystems, which are our life support system in many important ways, appear to be the most vulnerable to the harmful effects of climate change...

Major alterations to natural ecosystems due to climate change could possibly have negative consequences for our economy, which depends in part on the sustained bounty of our nation's lands, waters, and native plant and animal communities.



SUMMARY

CLIMATE CHANGE AND OUR NATION

The magnitude of climate change impacts depends on time period and geographic scale. Short-term impacts differ from long-term impacts, and regional and local level impacts are much more pronounced than those at the national level.

For the nation as a whole, direct economic impacts are likely to be modest, while in some places, economic losses or gains are likely to be large. For example, while crop yields are likely to increase at the national scale over the next few decades, large increases or decreases in yields of specific crops in particular places are likely.

Through time, climate change will possibly affect the same resource in opposite ways. For example, forest productivity is likely to increase in the short term, while over the longer term, changes in processes such as fire, insects, drought, and disease will possibly decrease forest productivity.

Adaptation measures can,in many cases, reduce the magnitude of harmful impacts or take advantage of beneficial impacts. For example,in agriculture,many farmers will probably be able to alter cropping and management practices. Roads,bridges, buildings,and other long-lived infrastructure can be designed taking projected climate change into account. Adaptations,however, can involve trade-offs,and do involve costs. For example,the benefits of building sea walls to prevent sea-level rise from disrupting human coastal communities will need to be weighed against the economic and ecological costs of seawall construction. The ecological costs could be high as seawalls prevent the inland shifting of coastal wetlands in response to sea-level rise, resulting in the loss of vital fish and bird habitat and other wetland functions,such as protecting shorelines from damage due to storm surges. Protecting against any increased risk of water-borne and insect-borne diseases will require diligent maintenance of our public health system. Many adaptations, notably those that seek to reduce other environmental stresses such as pollution and habitat fragmentation,will have beneficial effects beyond those related to climate change.

Vulnerability in the US is linked to the fates of other nations,and we cannot evaluate national consequences due to climate variability and change without also considering the consequences of changes elswhere in the world. The US is linked to other nations in many ways,and both our vulnerabilities and our potential responses will likely depend in part on impacts and responses in other nations. For example,conflicts or mass migrations resulting from resource limits,health,and environmental stresses in more vulnerable nations could possibly pose challenges for global security and US policy. Effects of climate variability and change on US agriculture will depend critically on changes in agricultural productivity elsewhere,which can shift international patterns of food supply and demand. Climate-induced changes in water resources available for power generation,transportation,cities,and agriculture are likely to raise potentially delicate diplomatic issues with both Canada and Mexico.

This Assessment has identified many remaining uncertainties that limit our ability to understand fully the spectrum of potential consequences of climate change for our nation. To address these uncertainties,additional research is needed to improve our understanding of ecological and social processes that are sensitive to climate, ways of applying climate scenarios and reconstructions of past climates to the study of impacts,and assessment strategies and methods. Results from these research efforts will inform future assessments that will continue the process of building our understanding of humanity's impacts on climate,and climate's impacts on us.

KEY FINDINGS

1. Increased warming

Assuming continued growth in world greenhouse gas emissions, the primary climate models used in this Assessment project that temperatures in the US will rise 5-9ºF (3-5ºC) on average in the next 100 years. A wider range of outcomes is possible.

2. Differing regional impacts

Climate change will vary widely across the US. Temperature increases will vary somewhat from one region to the next. Heavy and extreme precipitation events are likely to become more frequent, yet some regions will get drier. The potential impacts of climate change will also vary widely across the nation.

3. Vulnerable ecosystems

Many ecosystems are highly vulnerable to the projected rate and magnitude of climate change. A few, such as alpine meadows in the Rocky Mountains and some barrier islands, are likely to disappear entirely in some areas. Others, such as forests of the Southeast, are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests. The goods and services lost through the disappearance or fragmentation of certain ecosystems are likely to be costly or impossible to replace.

4. Widespread water concerns

Water is an issue in every region, but the nature of the vulnerabilities varies. Drought is an important concern in every region. Floods and water quality are concerns in many regions. Snowpack changes are especially important in the West, Pacific Northwest, and Alaska.

5. Secure food supply

At the national level, the agriculture sector is likely to be able to adapt to climate change. Overall, US crop productivity is very likely to increase over the next few decades, but the gains will not be uniform across the nation. Falling prices and competitive pressures are very likely to stress some farmers, while benefiting consumers.

6. Near-term increase in forest growth

Forest productivity is likely to increase over the next several decades in some areas as trees respond to higher carbon dioxide levels. Over the longer term, changes in larger-scale processes such as fire, insects, droughts, and disease will possibly decrease forest productivity. In addition, climate change is likely to cause long-term shifts in forest species, such as sugar maples moving north out of the US.

7. Increased damage in coastal and permafrost areas

Climate change and the resulting rise in sea level are likely to exacerbate threats to buildings, roads, powerlines, and other infrastructure in climatically sensitive places. For example, infrastructure damage is related to permafrost melting in Alaska, and to sea-level rise and storm surge in low-lying coastal areas.

8. Adaptation determines health outcomes

A range of negative health impacts is possible from climate change, but adaptation is likely to help protect much of the US population. Maintaining our nation's public health and community infrastructure, from water treatment systems to emergency shelters, will be important for minimizing the impacts of water-borne diseases, heat stress, air pollution, extreme weather events, and diseases transmitted by insects, ticks, and rodents.

9. Other stresses magnified by climate change

Climate change will very likely magnify the cumulative impacts of other stresses, such as air and water pollution and habitat destruction due to human development patterns. For some systems, such as coral reefs, the combined effects of climate change and other stresses are very likely to exceed a critical threshold, bringing large, possibly irreversible impacts.

10. Uncertainties remain and surprises are expected

Significant uncertainties remain in the science underlying regional climate changes and their impacts. Further research would improve understanding and our ability to project societal and ecosystem impacts and to provide the public with additional useful information about options for adaptation. However, it is likely that some aspects and impacts of climate change will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.

IMPACTS OF CLIMATE CHANGE

It is very likely that the US will get substantially warmer. Temperatures are projected to rise more rapidly in the next one hundred years than in the last 10,000 years. It is also very likely that there will be more precipitation overall, with more of it coming in heavy downpours. In spite of this, some areas are likely to get drier as increased evaporation due to higher temperatures outpaces increased precipitation. Droughts and flash floods are likely to become more frequent and intense.

PERMAFROST AREAS

It is very probable that rising temperatures will cause further permafrost thawing, damaging roads, buildings, and forests in Alaska.

FORESTRY

Timber inventories are likely to increase over the 21st century. Hardwood productivity is likely to increase more than softwood productivity in some regions, including the Southeast.

SPECIES DIVERSITY

While it is possible that some species will adapt to changes in climate by shifting their ranges, human and geographic barriers,and the presence of invasive non-native species will limit the degree of adaptation that can occur. Losses in local biodiversity are likely to accelerate towards the end of the 21st century.

WATER SUPPLY

Reduced summer runoff, increased winter runoff, and increased demands are likely to compound current stresses on water supplies and flood management,especially in the western US.

ISLANDS

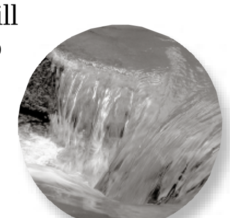
Sea-level rise and storm surges will very likely threaten public health and safety and possibly reduce the availability of fresh water.

CORAL REEFS

Increased CO_2 and ocean temperatures,especially combined with other stresses, will possibly exacerbate coral reef bleaching and die-off.

FRESHWATER ECOSYSTEMS

Increases in water temperature and changes in seasonal patterns of runoff will very likely disturb fish habitat and affect recreational uses of lakes,streams, and wetlands.



FOREST ECOSYSTEMS

Forest growth is likely to increase in many regions, at least over the next several decades. Over the next century, tree and animal species' ranges will probably shift in response to the changing climate. Some forests are likely to become more susceptible to fire and pests.

AGRICULTURE

The Nation's food supply is likely to remain secure.The prices paid by consumers and the profit margins for food producers are likely to continue to drop.

HUMAN POPULATIONS

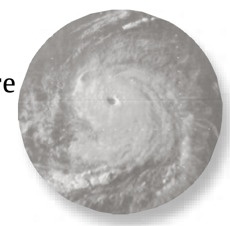
Heat waves are very likely to increase in frequency, resulting in more heat-related stresses. Milder winters are likely to reduce cold-related stresses in some areas.

COASTAL ECOSYSTEMS

Sea-level rise is very likely to cause the loss of some barrier beaches,islands, marshes,and coastal forests, throughout the 21st century.

EXTREME EVENTS

It is very likely that more rain will come in heavy downpours,increasing the risk of flash floods.



COASTAL COMMUNITIES AND INFRASTRUCTURE

Coastal inundation from storm surges combined with rising sea level will very likely increase threats to water and sewer systems,transportation and communication systems,homes,and other buildings.

RARE ECOSYSTEMS

Alpine meadows,mangroves,and tropical mountain forests in some locations are likely to disappear because the new local climate will not support them or there are barriers to their movement.

Adaptation

There are substantial opportunities to minimize the negative impacts and maximize the benefits of climate change through adaptation. Examples include cultivating varieties of crops, trees, and livestock that are better suited to hotter conditions. This report includes an initial identification of potential adaptation strategies, but an analysis of their effectiveness, practicality, and costs was not considered in this Assessment.