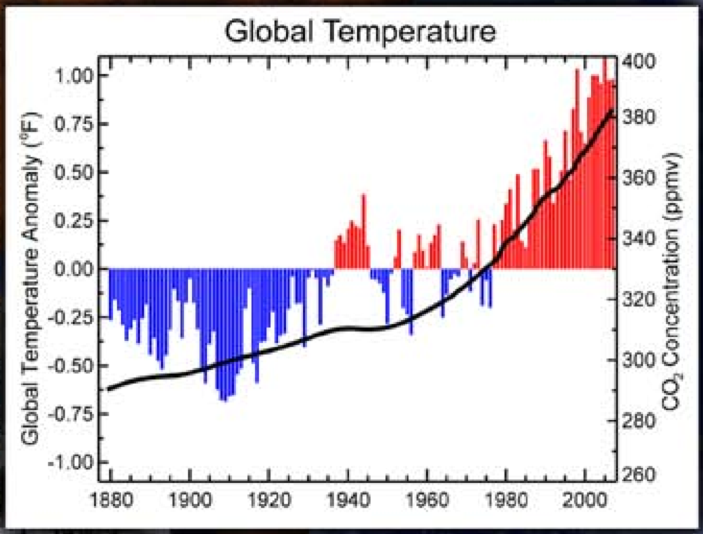
Global Climate Change Impacts in the United States



U.S. Climate Change Science Program
Unified Synthesis Product

First Draft - July 2008

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Global Climate Change Impacts in the United States

Unified Synthesis Product

Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

Edited by:
Susan J. Hassol, Thomas R. Karl, Jerry M. Melillo,
and Thomas C. Peterson

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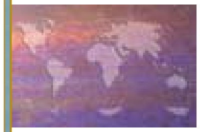

National Level Climate Impacts

Climate Change Impacts by Sector

DEPARTMENT OF COMMERCE · UNITED STATES OF AMERICA

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

transmittal letter to congress

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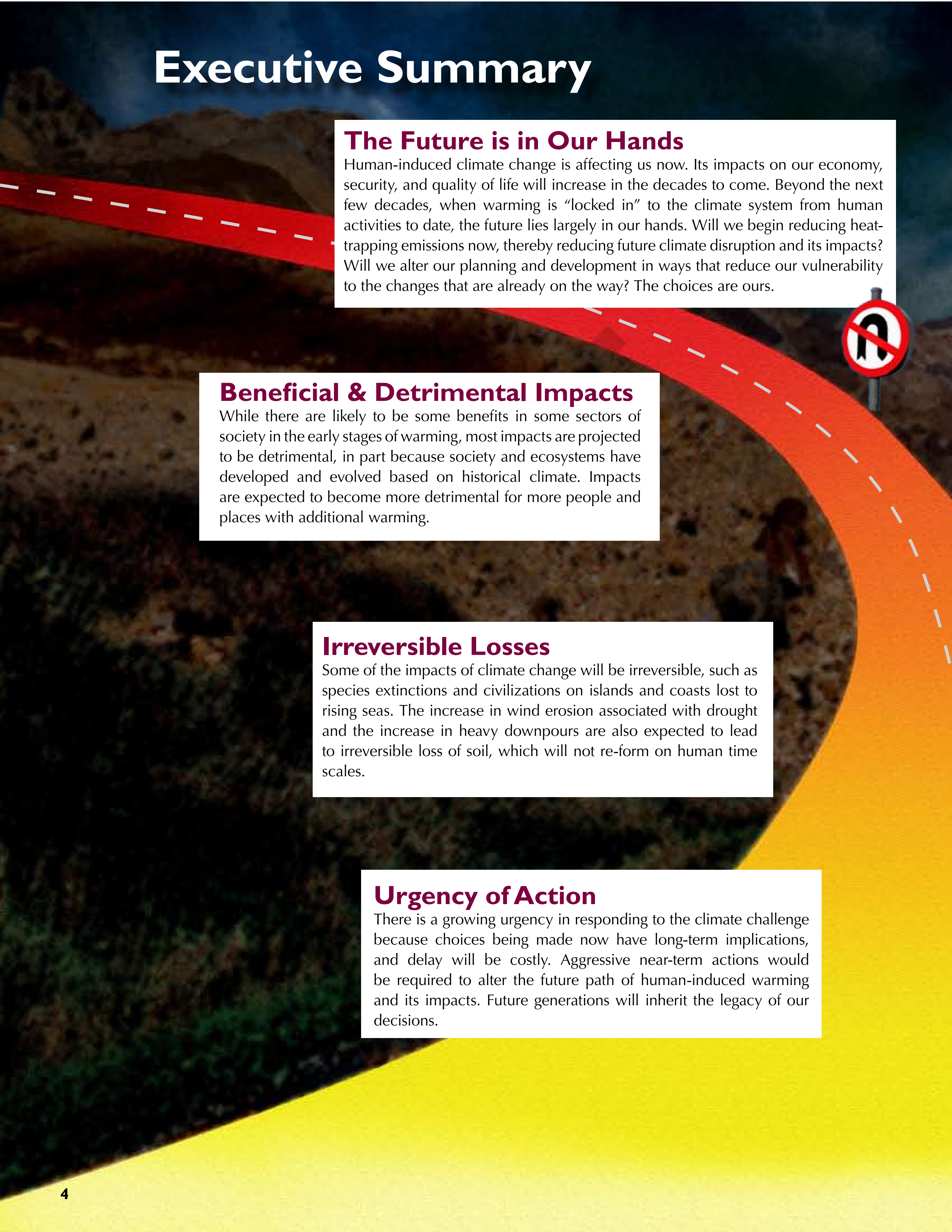
This Synthesis and Assessment Product described in the U.S. Climate Change Science Program (CCSP) Strategic Plan, was prepared in accordance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and the information quality act guidelines issued by the Department of Commerce and NOAA pursuant to Section 515 <http://www.noaanews.noaa.gov/stories/iq.htm>). The CCSP Interagency Committee relies on Department of Commerce and NOAA certifications regarding compliance with Section 515 and Department guidelines as the basis for determining that this product conforms with Section 515. For purposes of compliance with Section 515, this CCSP Synthesis and Assessment Product is an "interpreted product" as that term is used in NOAA guidelines and is classified as "highly influential". This document does not express any regulatory policies of the United States or any of its agencies, or provide recommendations for regulatory action.

Executive Summary



The Future is in Our Hands

Human-induced climate change is affecting us now. Its impacts on our economy, security, and quality of life will increase in the decades to come. Beyond the next few decades, when warming is "locked in" to the climate system from human activities to date, the future lies largely in our hands. Will we begin reducing heat-trapping emissions now, thereby reducing future climate disruption and its impacts? Will we alter our planning and development in ways that reduce our vulnerability to the changes that are already on the way? The choices are ours.

Beneficial & Detrimental Impacts

While there are likely to be some benefits in some sectors of society in the early stages of warming, most impacts are projected to be detrimental, in part because society and ecosystems have developed and evolved based on historical climate. Impacts are expected to become more detrimental for more people and places with additional warming.

Irreversible Losses

Some of the impacts of climate change will be irreversible, such as species extinctions and civilizations on islands and coasts lost to rising seas. The increase in wind erosion associated with drought and the increase in heavy downpours are also expected to lead to irreversible loss of soil, which will not re-form on human time scales.

Urgency of Action

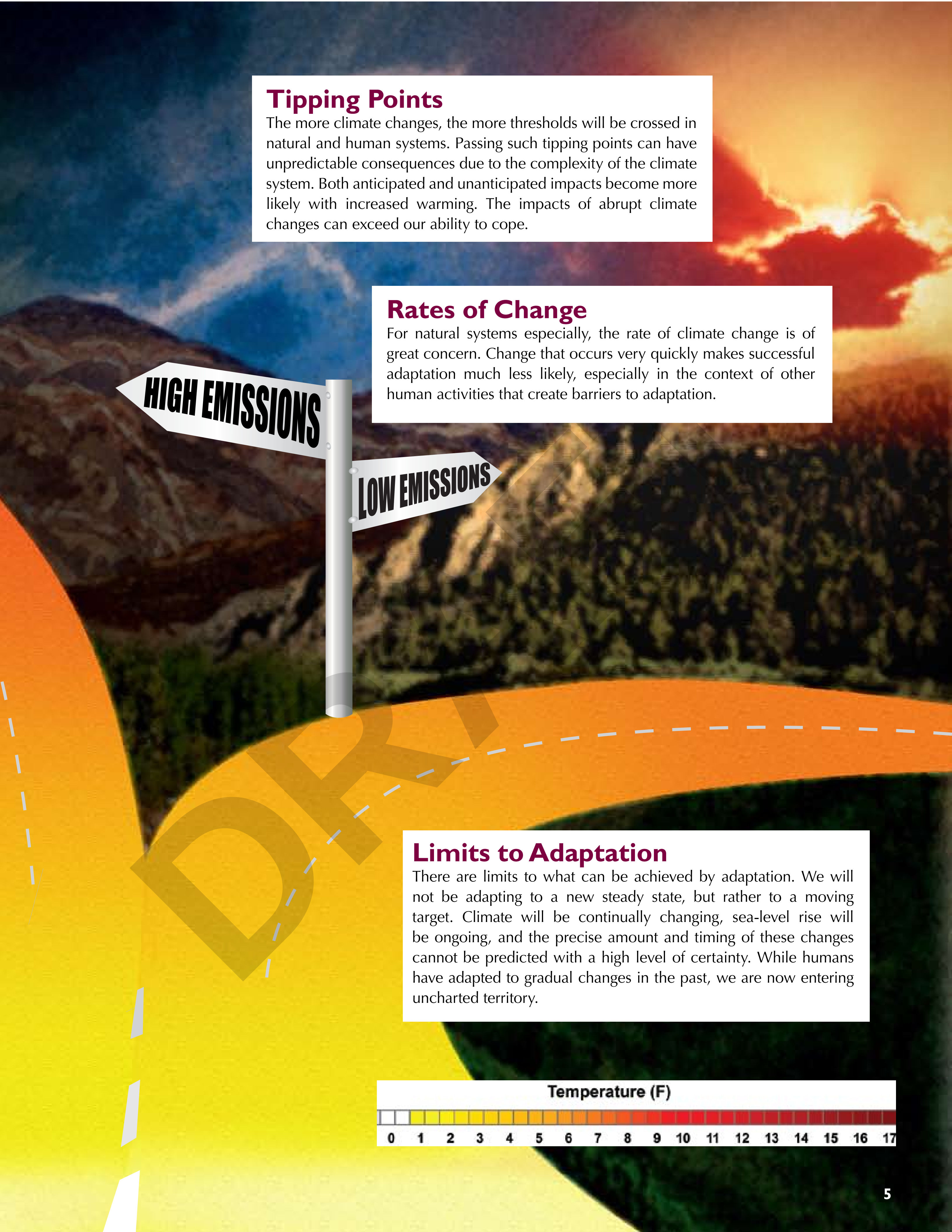
There is a growing urgency in responding to the climate challenge because choices being made now have long-term implications, and delay will be costly. Aggressive near-term actions would be required to alter the future path of human-induced warming and its impacts. Future generations will inherit the legacy of our decisions.

Tipping Points

The more climate changes, the more thresholds will be crossed in natural and human systems. Passing such tipping points can have unpredictable consequences due to the complexity of the climate system. Both anticipated and unanticipated impacts become more likely with increased warming. The impacts of abrupt climate changes can exceed our ability to cope.

Rates of Change

For natural systems especially, the rate of climate change is of great concern. Change that occurs very quickly makes successful adaptation much less likely, especially in the context of other human activities that create barriers to adaptation.



Limits to Adaptation

There are limits to what can be achieved by adaptation. We will not be adapting to a new steady state, but rather to a moving target. Climate will be continually changing, sea-level rise will be ongoing, and the precise amount and timing of these changes cannot be predicted with a high level of certainty. While humans have adapted to gradual changes in the past, we are now entering uncharted territory.

Key Findings

Once considered a problem mainly for the future, climate change is now upon us. People are at the heart of this problem: we are causing it, and we are being affected by it. The rapid onset of many aspects of climate change highlights the urgency of confronting this challenge without further delay. The choices that we make now will influence current and future emissions of heat-trapping gases, and can help to reduce future warming. Likewise, our decisions on whether and how to adapt to the degree of warming that is already inevitable can help us reduce the impacts of future warming.

1. **Human-induced climate change and its impacts are apparent now throughout the United States.**
- Global warming is unequivocal and is due primarily to human-induced emissions of heat-trapping gases and other pollutants[1].
- Observed changes in the United States include temperature increases, sea-level rise, increased heavy downpours, rapidly retreating glaciers, regional droughts, substantial changes in sensitive wildlife, earlier snowmelt, and altered timing and amount of river flows.
- Impacts of these changes are apparent in many facets of society including health, water, food, energy, and quality of life.

2. **Many climatic changes are occurring faster than projected even a few years ago.** **New**
- Global emissions of heat-trapping gases are now increasing even more rapidly than the highest emissions scenario scientists have been analyzing.
- Arctic sea ice and the large ice sheets on Greenland and parts of Antarctica are melting faster than expected.

3. **The degree to which future climate will change, and the scope and magnitude of the impacts, depend on choices made now.**
- Another 1°F of warming in the next few decades (on top of the observed 1.5°F rise) is already locked in due to past emissions.
- The amount of warming we will experience beyond the next few decades depends upon choices about emissions made now and in the near future.
- Lower emissions of heat-trapping gases will result in less climate change and related impacts.

4. **Extreme weather and climate are having increasing impacts on society.**
- The United States has experienced increases in heat waves, wildfires, heavy downpours, and in some regions, droughts, all of which are disrupting our lives.
- Extreme events affect every aspect of society and nature including human health, energy, transportation, agriculture, ecosystems, and water resources.
- Atlantic hurricane intensity has increased in recent decades and additional future increases are projected.

5. **Sea-level rise and storm surges place many U.S. coastal regions at increasing risk.**
- The low-lying East Coast and Gulf Coast of the United States are vulnerable to combined effects of sea-level rise, storm surges, and hurricanes.
- Alaska's coast is vulnerable to the effects of sea-ice retreat, thawing of coastal permafrost, and rising sea level, all of which are caused by warming, and combine to increase coastal erosion.
- Sea-level rise threatens the long-term viability of island communities by exacerbating the impacts of coastal storms, flooding infrastructure and ecosystems, and contaminating freshwater supplies with seawater.

6. Assuring an adequate and clean water supply will be an increasing challenge in many parts of the United States.

- Most of the West's surface water comes from snowpack, which is declining as more precipitation falls as rain and snowpack melts earlier, leaving less water available for summer when it is needed most.
- Growing populations and changing precipitation patterns will increase competition among urban, industrial, agricultural, and natural ecosystem water needs in regions where overall water supply declines.

7. Interactions among climate-related and other stresses will present complex challenges to society.

- Simultaneous and back-to-back extreme weather events can amplify impacts, challenging our response capabilities.
- Climate change can combine with other stresses including pollution, invasive species, and the overuse of resources to create impacts larger than any of these alone.
- Trade-offs will be necessary. For example, increasing water scarcity in some regions will force hard choices about the allocation of water for growing food, producing electricity, providing for urban uses, and protecting ecosystems.

8. Our vulnerability to climate change has been increased by some of our decisions.

- Population and development patterns have put more people in places that are vulnerable to climate change impacts.
- U.S. population has grown rapidly in cities on the Atlantic and Gulf coasts, which are vulnerable to extreme heat, sea-level rise, hurricanes, and storm surge.
- There has been very rapid population growth in arid western states where water is projected to become increasingly scarce in a warming world.

9. Historical climate and weather patterns are no longer an adequate guide to the future.

- Planning for providing water, energy, transportation, and other services has assumed the future would be like the past; this is no longer justifiable.
- Long-lived infrastructure, from power plants to roads and buildings, must be designed and built taking climate change into account.
- Long term planning will have to continually incorporate the latest information, as climate will be ever changing, requiring adaptation strategies to constantly evolve.

10. Responses to climate change entail reducing emissions to limit future warming and adapting to the changes that are unavoidable.

- Large cuts in emissions would be required to limit warming to the low end of the range of scenarios, making successful adaptation more likely.
- There are limits to adaptation. For example, the financial and technical challenges of defending coasts against sea-level rise under high emissions scenarios would probably result in the inundation and abandonment of many areas.
- Applying the best scientific information can help avoid unintended consequences of our responses to climate change.

Summary of Impacts on Sectors

SOCIETY

- Population movements and development choices are among the societal changes that are making more Americans vulnerable to climate change impacts.
- Vulnerabilities to climate change impacts are greater for those who have few resources and few choices.
- Climate change will affect the tourism and recreation industries in ways that reduce opportunities for many activities that Americans hold dear.
- Cities, both their residents and their infrastructure, have unique vulnerabilities to climate change.
- The insurance industry is particularly vulnerable to increasing extreme weather events, but can also help society manage the risks.

HUMAN HEALTH

- Significant increases in illness and death related to extreme heat are projected, along with small decreases in cold-related impacts.
- Health impacts due to reduced air quality are projected to be an increasing problem, especially in urban areas.
- Physical and mental health impacts due to extreme weather events are projected to increase.
- Infectious diseases borne by food, water, and insects are projected to increase.
- Allergies and asthma are on the rise, with climate change expected to play an increasing role in the future.
- Certain groups, including children, the elderly, and the poor, are most vulnerable to the range of health effects.

ENERGY

- Warming will be accompanied by significant increases in electricity use and peak demand in most regions, due to increased demand for air conditioning.
- Energy production is dependent upon reliable water supply.
- Rising temperatures decrease power plant efficiency.
- Energy production and delivery systems are vulnerable to sea-level rise and extreme weather events in many regions.
- Climate change is likely to affect some renewable energy sources, especially hydropower.

TRANSPORTATION

- Sea-level rise and storm surges are projected to result in major impacts, including flooding of coastal airports, roads, rail lines, and tunnels.
- Increasingly intense downpours and related flooding will cause disruptions and delays in air, rail, and road transportation.
- The increase in extreme heat will limit some operations and cause pavement and track damage. Decreased extreme cold will confer benefits.
- Increased intensity of strong hurricanes would lead to more evacuations, damages, transportation interruptions, and a greater probability of infrastructure failure.
- Arctic warming reduces sea ice, lengthening the ocean transport season. Permafrost thaw in Alaska damages infrastructure. The ice road season becomes shorter.

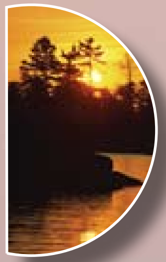
WATER RESOURCES

- Climate change will continue to alter the water cycle, affecting where, when, and how much water is available for human and ecosystem uses.
- The quality and quantity of surface water and groundwater are affected by a changing climate.
- Climate change will add yet another burden to already-stressed water systems.
- The past century is no longer a reasonable guide to the future for water management.

AGRICULTURE AND LAND RESOURCES

- Crops show mixed responses to lower levels of warming, but higher levels of warming often negatively affect growth and yields.
- Extreme events such as heavy downpours and droughts reduce crop yields.
- Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from rising carbon dioxide, increasing stress on crop plants and requiring more pesticide and herbicide use.
- Forage quality in pasture and rangeland generally declines, reducing the land's ability to supply adequate livestock feed.
- Increased heat, disease, and weather extremes reduce livestock productivity.
- Warming and rising carbon dioxide increase forest growth, but more insect outbreaks, fire, and drought have negative effects.
- Deserts and dry lands become hotter and drier, feeding a self-reinforcing cycle of invasive plants, fire, and erosion.

NATURAL ENVIRONMENT AND BIODIVERSITY

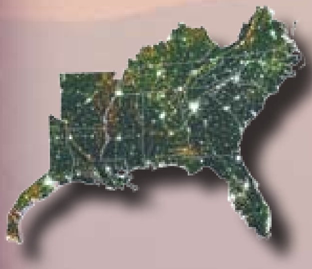


- Ecosystem processes have been affected by climate change.
- There have been large-scale shifts in species ranges, the timing of the seasons, and animal migration; further such changes are projected.
- There have been increases in fire, insect pests, disease pathogens, and invasive weed species, and more are projected.
- Coastal and near-coastal ecosystems including wetlands and coral reefs are especially vulnerable to the impacts of climate change.
- Mountain species and cold-water fishes like salmon and trout are particularly sensitive to climate change impacts.
- Arctic sea ice ecosystems are extremely vulnerable to warming.

Summary of Impacts on Regions

NORTHWEST

- Declining springtime snowpack leads to reduced summer streamflows, straining water supplies.
- Increased insect outbreaks and wildfires, combined with changing species composition in forests will pose challenges for unique ecosystems.
- Salmon and other cold-water species experience additional stresses due to rising water temperatures and declining summer streamflows.
- Human health threats due to heat waves, reduced air quality, and insect-borne diseases are projected to increase.
- Sea-level rise will result in increased erosion along vulnerable coastlines.



SOUTHEAST

- Projected increases in air and water temperatures will cause heat-related stresses.
- Decreased water availability will impact the economy as well as natural systems.
- Accelerated sea-level rise and increased tropical storm intensity will have serious impacts.
- Ecological thresholds are likely to be crossed, causing the rapid restructuring of ecosystems and the services they provide.
- Quality of life will be adversely affected by increasing heat stress, water scarcity, severe weather events, and reduced availability of insurance for at-risk properties.

ALASKA

- Summers are becoming longer and drier.
- Insect outbreaks and wildfires are increasing with warming.
- Lakes are declining in area.
- Thawing permafrost damages roads, runways, water and sewer systems, and other infrastructure.
- Coastal storms increase risks to villages and fishing fleets.
- Displacement of marine species will impact key fisheries.

Map for islands
is still under
development

ISLANDS

- Anticipated reductions in the availability of freshwater will have significant implications for island communities, economies, and resources.
- Island communities, infrastructure, and ecosystems are vulnerable to coastal inundation due to sea-level rise and coastal storms.
- Climate changes affecting coastal and marine ecosystems will have major implications for tourism and fisheries.

MIDWEST

- Public health and quality of life, especially in cities, will be negatively affected by increasing heat waves, reduced air quality, and insect- and water-borne diseases.
- Under higher emissions scenarios, significant reductions in Great Lakes water levels will impact shipping, infrastructure, beaches, and ecosystems.
- Increasing precipitation in winter and spring, more heavy downpours, and greater evaporation in summer will mean more periods of both floods and water deficits.
- While a longer growing season provides the potential for increased crop yields, increases in heat waves, floods, droughts, insects, and weeds will present increasing challenges to crops, livestock, and forests.
- Native species will face increasing threats from rapidly changing climate conditions, pests, diseases, and invasive species moving in from warmer regions.

SOUTHWEST

- Water supplies will become increasingly scarce, calling for difficult trade-offs among competing uses.
- Human health concerns include increases in heat waves, reduced air quality, and the spread of diseases from the south.
- Ranching and agriculture decline as climate heats up and water is converted to urban uses for the rapidly growing population.
- Increasing drought and fire are beginning to transform the landscape, threatening biodiversity and protected areas.

NORTHEAST

- Extreme heat and declining air quality are projected to pose increasing problems for human health, especially in urban areas.
- Agricultural production, including dairy, fruit, and maple syrup, will be increasingly affected as favorable climates shift.
- Severe floods due to sea-level rise and heavy downpours are projected to occur more frequently.
- The projected reduction in snow cover will affect winter recreation and the industries that rely upon it.
- The center of lobster fisheries is projected to continue its northward shift and the cod fishery on Georges Bank is likely to be diminished.

GREAT PLAINS

- Projections of increasing temperature, evaporation, and drought frequency exacerbate concerns regarding the availability of water in a region dependent on a declining groundwater source.
- Agriculture, ranching, and natural lands, already under pressure due to an increasingly limited water supply, will also be stressed by rising temperatures.
- Climate change is likely to affect native plant and animal species by altering key habitats such as the wetland ecosystems known as prairie potholes or playa lakes.
- Ongoing shifts in population from rural to urban centers are expected to increase the vulnerability of Great Plains inhabitants to climate change.

COASTS

- Significant sea-level rise and storm surge will affect coastal cities and ecosystems around the nation, with low-lying and subsiding areas most vulnerable.
- Increases in spring runoff and warmer coastal waters will exacerbate the seasonal reduction in dissolved oxygen that results from excess nitrogen from agriculture.
- Warming coastal waters will allow new invasions by non-native species that occur through ship transport and other human activities.
- Rising water temperatures and ocean acidification due to increasing atmospheric carbon dioxide present major additional stresses to coral reefs, resulting in significant die-offs and limited recovery.
- Changing coastal currents will result in shifts in fisheries and cause surprising changes such as oxygen-depleted waters that either kill marine species or cause them to leave the area.

Response Strategies

Most scientific research has focused on understanding the nature, causes, and impacts of climate change, and estimating the human contribution to these changes. Considerably less attention has been paid to the portfolio of approaches that will be needed to respond to the problem of human-induced climate change. Items in this portfolio include reducing emissions of heat-trapping gases, as well as developing measures to adapt to the amount of warming that is not prevented through such reductions. Other potential options, such as intentional manipulation of aspects of the climate system in an attempt to counteract the warming influence of heat-trapping gases, will not be discussed here, though it should be mentioned that such options must be evaluated for unintended consequences.

Throughout this report, the impacts of climate change will be viewed through the lens of our possible responses. Comparing impacts for low and high emission scenarios highlights the choices society faces with regard to levels of heat-trapping emissions. Options for reducing these emissions are often referred to as "mitigation" and include improved energy efficiency, using energy sources that don't produce carbon dioxide or produce less of it, capturing and storing carbon dioxide from fossil fuel use, and so on.

The other major category of response strategies is known as "adaptation," which refers to changes made to better respond to present or future circumstances. This includes deliberately adjusting to actual or anticipated changed conditions to avoid or reduce negative impacts or to take advantage of positive ones. For example, a farmer might switch to growing a different crop variety better suited to warmer or drier conditions. A company might relocate key business centers away from coastal areas vulnerable to sea-level rise and hurricanes. A community might alter its zoning and building codes to place fewer structures in harm's way and make buildings less vulnerable to damage from floods, fires, and other extreme events.

One of the key goals of adaptation is to make a community or system better able to withstand the kinds of perturbations that are expected. Adaptation can be thought of as improved planning, using the best available information about future climatic conditions, and considering climate change in the context of other factors that affect development decisions, particularly the challenge of planning in the face of competing economic and social objectives.

The more we mitigate (reduce emissions), the less climate change we'll experience and the less severe the impacts will be, and thus, the less adaptation will be required. However, no matter how aggressively emissions are reduced, the world will still experience some continued climate change and resulting impacts. This is true for several reasons. First, elevated concentrations of greenhouse gases already in the atmosphere will remain there for many decades, with some fraction of the carbon dioxide produced by fossil fuel burning staying in the atmosphere for many thousands of years. Second, the climate system has significant inertia and can take many centuries to fully respond to such perturbations. And third, the drivers that determine emissions, such as energy supply systems, cannot be changed overnight. Consequently, some degree of adaptation is inevitable.

Unless we explicitly plan for climate change, including reducing emissions and reducing vulnerabilities, we are likely to find that we will reach the limits of our adaptive capacity. Some communities, states, sectors, and the nation as a whole have a generally high capacity to adapt to projected changes in climate, but adaptive capacity is unequal across the nation. Future adaptation and adaptive capacity will be influenced by development decisions implemented in the near and long term in various regions within the United States and other countries.

There are potential synergies between mitigation and adaptation. For example, making buildings more energy efficient makes them more comfortable in extreme heat while also reducing energy use. In addition, some mitigation and adaptation options also produce other benefits to society, such as reducing health risks, and creating jobs or other economic benefits.

Some communities and businesses are developing comprehensive plans to both mitigate climate change by reducing their emissions and to reduce their vulnerability to climate change by pursuing adaptations. Mitigation strategies have been and are being explored extensively by international bodies such as the Intergovernmental Panel on Climate Change and the Global Energy Assessment and will not be a significant focus of this report. Adaptation strategies, however, will be discussed throughout this document.

Despite what is widely assumed to be the considerable adaptive capacity of the United States, we have not always succeeded in avoiding significant losses and disruptions, for example, due to extreme weather events. There are many challenges and limits to adaptation. Some adaptations will be very expensive. We will be adapting to a moving target, as future climate will not be stationary but continually changing. And if emissions and thus warming are at the high end of future scenarios, some changes will be so large that adaptation is unlikely to be successful.

To date, adaptation responses have tended to be decentralized and uncoordinated with uneven results. This may be inevitable, at least at the beginning, for it is at the local level that the impacts of climate change and other stresses are experienced and it is also at the local level that the resources to respond are best understood and mobilized.

Examples of strategies communities can implement to adapt to climate change include:
- Introducing technological changes such as updating levees, water and sewer systems (to avoid increased contamination due to heavy downpours), pollution controls, insect controls, etc.
- Making institutional changes to improve coping capacity such as providing financial mechanisms for implementing adaptation strategies, improving coordination across jurisdictions, and developing targeted assistance programs
- Providing ecological buffers, such as preserving wetlands, that can prevent property damage and loss of life by taking advantage of natural ecosystem services
- Changing the location of people or activities through land-use policies and codes that encourage movement from more vulnerable areas to less vulnerable ones
- Changing the form of communities to encourage green spaces and green buildings through zoning and other measures

Examples of tools available for implementing these strategies include:
- Zoning, building codes, and design codes
- Early warning and disaster response systems
- Insurance pricing, terms, and conditions that send clearer signals to the market
- Incentives to encourage allowing high risk areas to return to a natural state

While adaptation takes place at the local scale, it is influenced by the larger scale context. For example, funding, information, and other support can be provided from higher levels of government, and large-scale regulatory and policy contexts can help resolve jurisdictional issues such as those relating to water supply management, licensing of facilities, forest management, and so on. National policies regarding codes, standards, insurance, and disaster management can support adaptation to climate change at the local level.

Criteria for effective adaptation include taking a long-term, holistic view of the problem and solutions in order to maximize effectiveness, minimize costs, and avoid unintended consequences. Such a holistic view recognizes that the pace and character of future development will influence adaptive capacity, and that improving adaptive capacity can support efforts to achieve economic and environmental objectives, as well as reducing impacts of climate change.

About this Report

Human-induced climate change is a major and growing concern to U.S. policymakers and citizens who need the best available science to inform their decisions. This report responds to that need by synthesizing the large and growing body of science that deals with how climate is changing, and the impacts of these changes on the United States, now and in the future.

The U.S. Climate Change Science Program, in coordination with the Office of Science and Technology Policy and Council on Environmental Quality, called for this report: a Unified Synthesis Product (USP) by a U.S. Department of Commerce Federal Advisory Committee operating under the authority of the Federal Advisory Committee Act. The Committee was composed of an expert team of scientists and supporting professionals.

This report is based on published, peer-reviewed data and reports including the Synthesis and Assessment Products completed by the U.S. Climate Change Science Program (CCSP, 2006 through 2008), the Intergovernmental Panel on Climate Change (IPCC, 2007) assessments, the U.S. National Assessment of the Consequences of Climate Variability and Change (NAST, 2000 through 2001), the Arctic Climate Impact Assessment (ACIA, 2004 through 2005), the National Research Council's Transportation Research Board report on the Potential Impacts of Climate Change and U.S. Transportation (NRC, 2008), and other peer-reviewed assessments.

To incorporate the latest findings and fill gaps, this report also draws directly from articles in peer-reviewed scientific journals as well as widely available government data and information compiled on a regular basis for public use, including census figures and statistics on energy usage and greenhouse gas emissions. The author team did not conduct original research for this report, but rather drew on existing peer-reviewed research. In order to convey the most relevant and up-to-date information possible, the report does contain summaries, tables, and graphics using updated data sets drawn from peer-reviewed literature and official government data.

This report seeks to synthesize this large body of information and draw the kinds of high-level insights that can come from such an activity.

While the primary focus of the report is on the impacts of climate change on the U.S., it also deals with some of the things society can do to respond to the climate challenge. Comparing the impacts of a range of heat-trapping gas emissions scenarios reveals differences related to the consequences of various emissions pathways, highlighting the choices we have with regard to human-induced emissions.

This report also explores some options for adapting to climate change and its impacts that could help in coping with the amount of additional warming that is inevitable as a result of past and ongoing emissions of heat-trapping gases and other human-induced changes. The report also highlights areas where inadequate scientific understanding hampers our ability to estimate likely future climate change impacts.

With regard to expressing the range of possible outcomes and identifying the likelihood of particular impacts, this report takes a plain language approach to expressing the expert judgment of the author team based on the best available evidence. For example, an outcome termed "likely" has at least a two-thirds chance of occurring; something termed "very likely," at least a 90 percent chance. In using these terms, the team has taken into consideration a wide range of information including the strength and consistency of the observed evidence, the range and consistency of model projections, the reliability of particular models as tested by various methods, and so on. Statements that are not qualified with such terms are deemed virtually certain. In cases where further qualifications regarding certainty are needed, endnotes are used for those descriptions.

The goal of this report is to make the key results of the enormous body of scientific information about climate change and its impacts on the United States accessible in a single plain-English document that can help inform public and private decision making at all levels.

CCSP 1.1 Temperature Trends
CCSP 1.2 Past Climate
CCSP 1.3 Re-Analysis
CCSP 2.1 GHG Emissions
CCSP 2.2 Carbon Cycle
CCSP 2.3 Aerosol Impacts
CCSP 2.4 Ozone Trends
CCSP 3.1 Climate Models
CCSP 3.2 Climate Projections
CCSP 3.3 Extremes
CCSP 3.4 Abrupt Climate Change

CCSP 4.1 Sea Level Rise
CCSP 4.2 Ecosystem Thresholds
CCSP 4.3 Impacts
CCSP 4.4 Ecosystem Adaptation
CCSP 4.5 Energy
CCSP 4.6 Health
CCSP 4.7 Transportation
CCSP 5.1 Data Uses & Limitations
CCSP 5.2 Uncertainty
CCSP 5.3 Decision Support

IPCC WG-1
IPCC WG-2
IPCC WG-3

ACIA Arctic Impacts
GAO Alaska Villages
NAST U.S. Impacts
NRC Transportation Impacts

PLACE HOLDER Recent Material
Original Synthesis

The icons above represent some of the major sources drawn upon for this synthesis report. A description of these sources appears in the back of this report. In the upper right hand corner of the introduction to each major section, the sources primarily drawn upon for that section are shown.

Global Climate Change

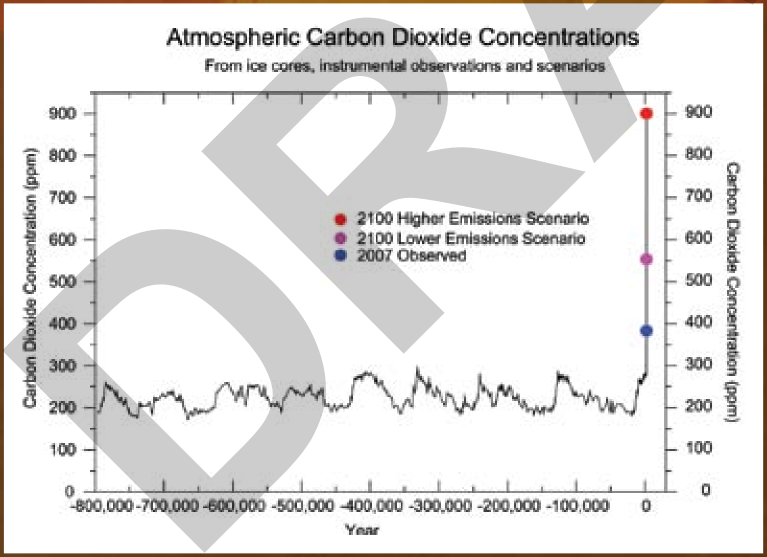
- Human-caused increases in the emissions of heat-trapping gases are responsible for most of the warming observed over the past 50 years.
- Changes in purely natural factors also influence climate, but cannot explain the warming of the past 50 years.
- Temperature and precipitation have increased over recent decades, along with some extreme weather events such as heat waves and heavy downpours.
- Warming is causing sea-level to rise as land-based ice melts and the warmer oceans expand.
- Arctic sea ice decline is accelerating.
- Many of these observed changes are occurring more rapidly than projected even a few years ago.
- The specific patterns of recent climatic change show that it is primarily human-induced.
- Global temperatures will continue to rise; how much depends on the amount of heat-trapping emissions and how sensitive the climate is to those emissions.
- Climate can also change abruptly, as is evident from ice core records of past climate.
- The human effect on climate can be minimized if emissions are sharply reduced.

Key Sources

- CCSP 1.1 Temperature Trends
- CCSP 1.2 Past Climate
- CCSP 1.3 Re-Analysis
- CCSP 2.1 GHG Emissions
- CCSP 2.2 Carbon Cycle
- CCSP 2.3 Aerosol Impacts
- CCSP 2.4 Ozone Trends
- CCSP 3.1 Climate Models
- CCSP 3.3 Extremes
- CCSP 3.4 Abrupt Climate Change
- CCSP 4.1 Sea Level Rise
- IPCC WG-1

This introduction to global climate change is a primer on what has been happening to global climate and why, and what is projected to happen in the future. While this report focuses on climate change impacts in the United States, understanding these changes necessarily requires an understanding of the Earth as a system, including the global climate. Impacts, while often local, arise from changes in this global system.

Some continued warming of the planet is inevitable over the next few decades. The amount of warming that we actually experience will be determined largely by the choices made now and in the near future. Lower amounts of heat-trapping emissions will yield less future warming, while higher amounts will result in more warming and more severe impacts on our society and economy as well as the natural world.

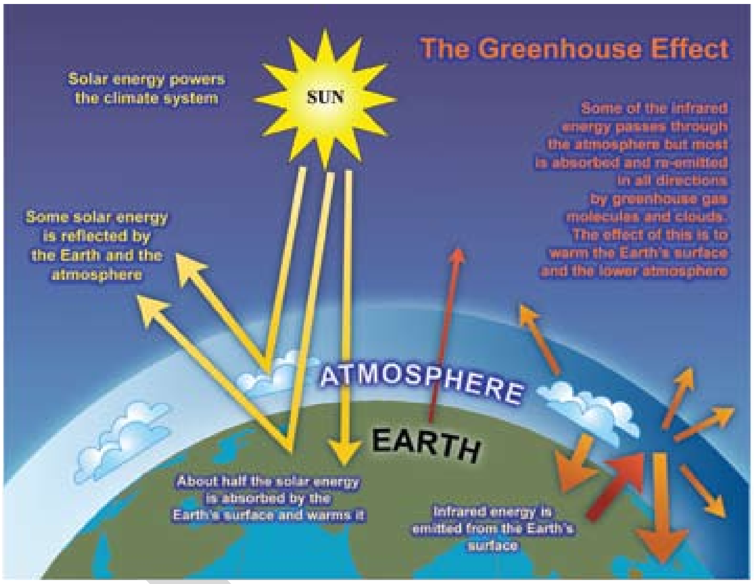


An Antarctic ice core provides a look at the past 800,000 years of Earth's carbon dioxide concentrations, a central factor in our planet's climate. Over this long period, atmospheric carbon dioxide levels varied within a range of 170 to 300 parts per million. Carbon dioxide concentration is now far outside of that range, 30 percent higher than the highest previous point, at over 380 parts per million. We are now in uncharted territory, and on a path that is moving us rapidly toward much higher levels.

The long record of temperature and carbon dioxide tells us something else as well: there is no natural cycle or process revealed in this long climate history that could have caused the global warming of the past 50 years.

Human-caused changes in the emissions of heat-trapping gases are responsible for most of the warming observed over the past 50 years.

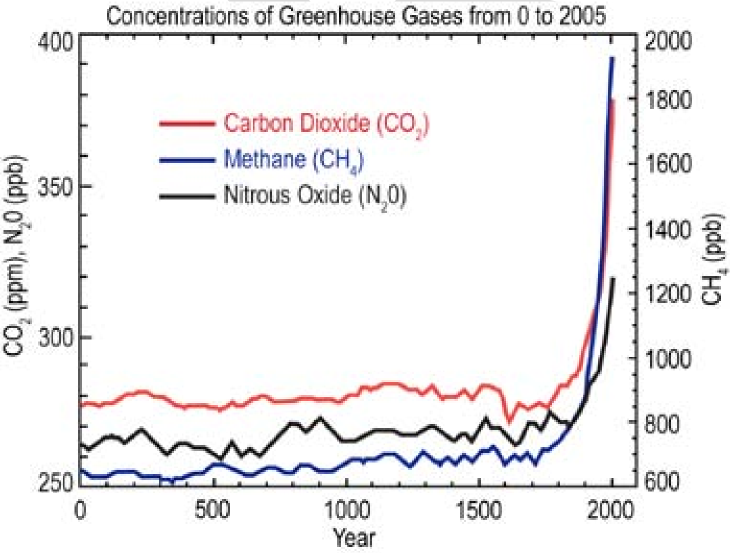
The Earth's atmosphere has a large natural "greenhouse effect." This arises because gases like water vapor, carbon dioxide, methane, and nitrous oxide, absorb heat radiated from Earth's surface. Without this natural greenhouse effect, the average surface temperature of the Earth would be about 60°F cooler. However, by burning fossil fuels (coal, oil and gas), we release additional heat-trapping gases into the atmosphere, thus intensifying the natural greenhouse effect, and changing the climate of our planet.



Earth's climate is influenced by a variety of factors, both human-induced and natural. Carbon dioxide, the principal driving factor in the warming of the past 50 years, has been building up in Earth's atmosphere since the beginning of the industrial era due to the burning of fossil fuels and the clearing of forests. Human activities have also increased the emissions of other greenhouse gases, such as methane, nitrous oxide, and halocarbons[1]. These emissions are thickening the blanket of heat-trapping gases in Earth's atmosphere, causing temperatures to rise.

Heat-trapping gases

Carbon dioxide has increased due to the use of fossil fuels in electricity generation, transportation, industrial processes, space and water heating, and in the manufacture of cement and other materials. Deforestation also releases carbon dioxide and also reduces its uptake by plants. Globally, over the past several decades, about 80 percent of human-induced carbon dioxide emissions come from the burning of fossil fuels, while about 20 percent results from deforestation. The concentration of carbon dioxide in the atmosphere has increased by 35 percent since the industrial revolution[2].

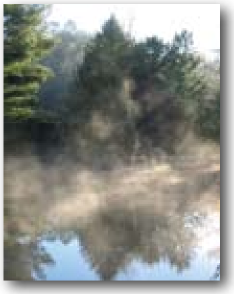


Increases in these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air.

Methane has increased as a result of the mining, transportation and use of coal, oil and natural gas, as well as from agriculture, raising livestock (which produce methane in their digestive tracts and from storage of manure under low oxygen conditions), and decomposing garbage in landfills.

Nitrous oxide is emitted from human activities such as fertilizer use and fossil fuel burning.

Halocarbon emissions come from the release of manmade chemicals such as chlorofluorocarbons (CFCs) like Freon®, which were used extensively in refrigeration and other industrial processes before their presence in the atmosphere was found to cause stratospheric ozone depletion. The abundance of these gases in the atmosphere is now decreasing as a result of international regulations designed to protect the ozone layer.
Ozone itself is a greenhouse gas, which is



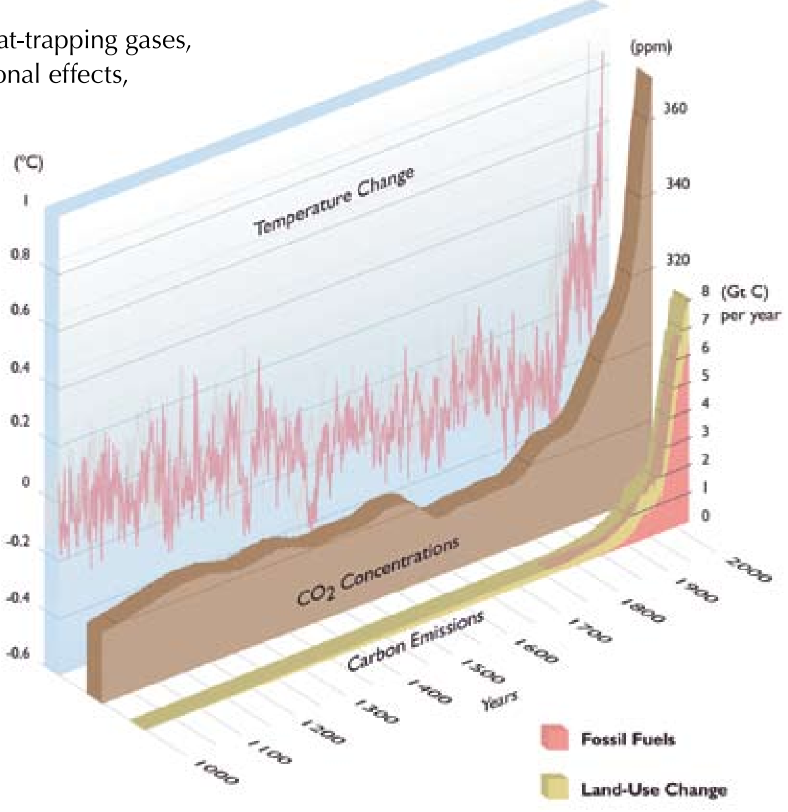
continually produced and destroyed in the atmosphere by chemical reactions. In the troposphere, the part of the atmosphere closest to the surface, human activities have increased ozone through the release of gases such as carbon monoxide, hydrocarbons, and nitrogen oxides, which chemically react to produce ozone in the presence of sunlight. In addition to trapping heat, ozone in the troposphere causes respiratory illnesses and other human health problems. In the stratosphere, far above Earth's surface, ozone protects life on Earth from exposure to excessive ultraviolet radiation from the Sun. As mentioned above, halocarbons released by human activities destroy ozone in the stratosphere and have caused the ozone hole over Antarctica.

Water vapor is the most important and abundant greenhouse gas in the atmosphere. Human activities have only a small direct effect on water vapor, but a large indirect effect. The indirect effect occurs because the warming caused by human-produced increases in greenhouse gases leads to an increase in water vapor (a warmer climate increases evaporation and allows the atmosphere to hold more moisture), which in turn leads to more warming. This is referred to as a "feedback loop." Thus, human-induced warming is indirectly responsible for the significant observed increase in water vapor that is fueling much of the warming.

Other human influences

In addition to the global-scale climate effects of heat-trapping gases, human activities also produce more local and regional effects, which may partially offset or increase some of the warming caused by greenhouse gases. One such influence on climate is caused by tiny particles that scientists call "aerosols" (not to be confused with aerosol sprays). In particular, burning coal and vegetation results in emissions of sulfur-containing compounds that act to directly reflect some of the Sun's heat away from the Earth. These aerosols also affect clouds, causing them to reflect away more of the Sun's heat, causing an additional indirect cooling effect. Another type of aerosol, often referred to as "soot," absorb incoming sunlight and trap heat. Thus aerosols can either mask or increase the warming caused by increased levels of greenhouse gases.

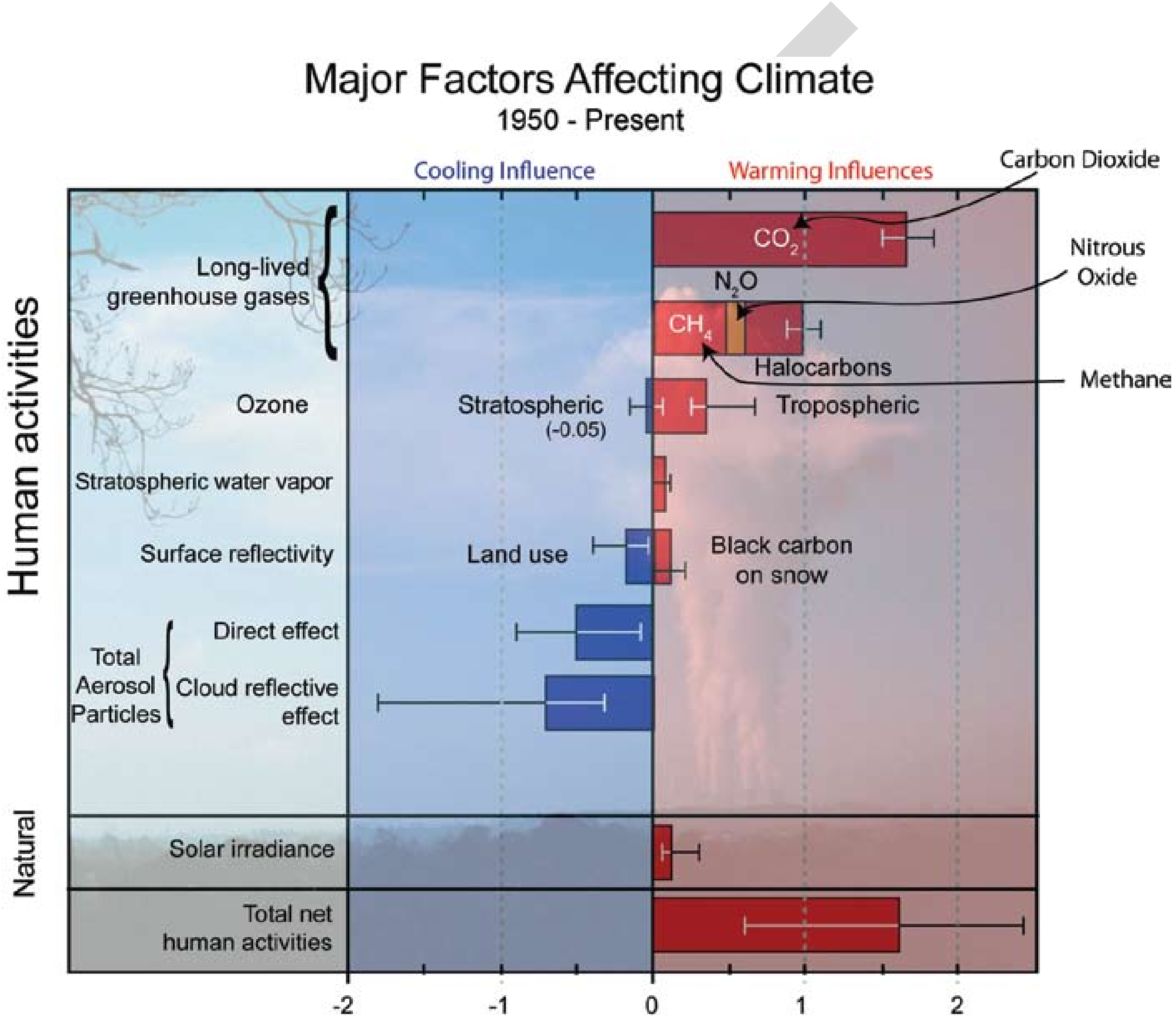
Human activities have also changed the land surface in ways that alter how much heat is reflected or absorbed by the surface. Such changes include the cutting and burning of forests and replacing wild lands with agriculture and cities. While these changes can have significant impacts locally, the net effect of these changes globally has probably been a slight cooling influence, as they have made the surface more reflective.



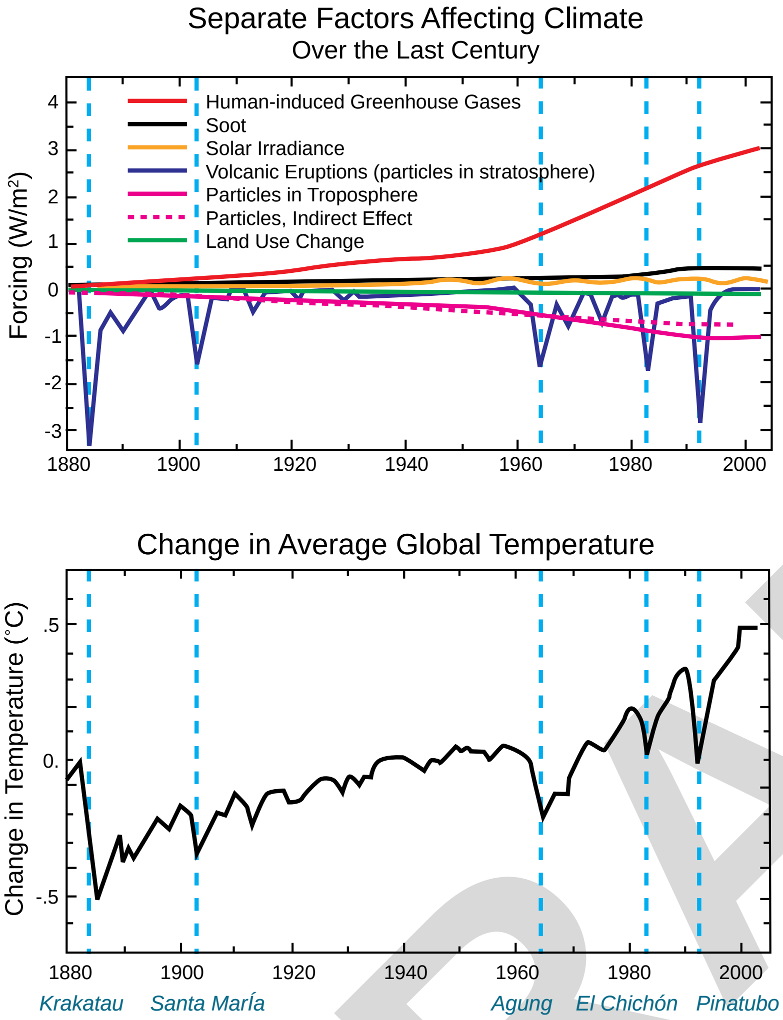
This 1000-year record tracks the rise in carbon emissions due to human activities (fossil fuel burning and land clearing) and the subsequent increase in atmospheric carbon dioxide (CO_2) concentrations and air temperatures. The earlier parts of the Northern Hemisphere temperature reconstruction shown here are derived from historical data, tree rings, and corals, while the later parts were directly measured. Measurements of CO_2 in air bubbles trapped in ice cores form the earlier part of the CO_2 record; direct atmospheric measurements of CO_2 began in 1957.

Changes in purely natural factors also influence climate, but cannot explain the warming of the past 50 years.

Two significant natural factors also influence climate: the Sun and volcanic eruptions. Over the past several decades, the time during which the human influence has become clear and global temperatures have risen sharply, the Sun's output, as measured by satellites, has followed its usual 11-year cycle of small ups and downs but with no net increase over the period. There have been several major volcanic eruptions that have had short-term cooling effects on climate lasting two to three years. These natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has been a slight cooling influence over this period, which is small compared to the large warming influence of the human-caused increases in heat-trapping gases.



The figure above shows the amount of warming influence (red bars) or cooling influence (blue bars) each factor has had on Earth's climate in the industrial age (about 1750 to the present) in watts per square meter. The top box includes all the major human-induced factors while the second box includes the Sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes during the industrial age, which is also natural, is too short-lived (1 to 2 years) to significantly affect climate over the long term. The bottom box shows that the total net effect of human activities is a strong warming influence. The thin lines on each bar indicate an estimate of the range of uncertainty.



The influences of various factors as they have affected climate over the past 125 years shown separately (after Hansen *et. al.*, 2005, top[38]) and combined together to produce net temperature changes (NCDC/NOAA observed global temperature, bottom). The strong warming effect caused by the human-induced greenhouse gases (red line on top graph) more than compensated for the cooling caused by particle pollution and a series of volcanic eruptions that produced short-term cooling effects. Five prominent volcanic eruptions that caused temporary cooling are marked by the blue dashed lines and labeled at the bottom of the figure. Changes in the Sun's output over time are shown as the wiggly yellow line that reflects the 11-year solar cycle but no upward or downward trend.

Carbon release and uptake

Once carbon dioxide is emitted to the atmosphere, some of it is absorbed by the oceans and by vegetation on land; about 45 percent of the carbon dioxide emitted by human activities in the last 50 years has been taken up by these natural "sinks." The rest has remained in the air, increasing the atmospheric concentration[3]. It is thus important to understand not only how much carbon dioxide is emitted, but also how much is taken up, over what time scales, and how these sources and sinks of carbon dioxide might change as climate continues to warm. A significant fraction of the carbon dioxide emitted by human activities remains in the atmosphere for thousands of years, and some of it will be there for hundreds of thousands of years[4].

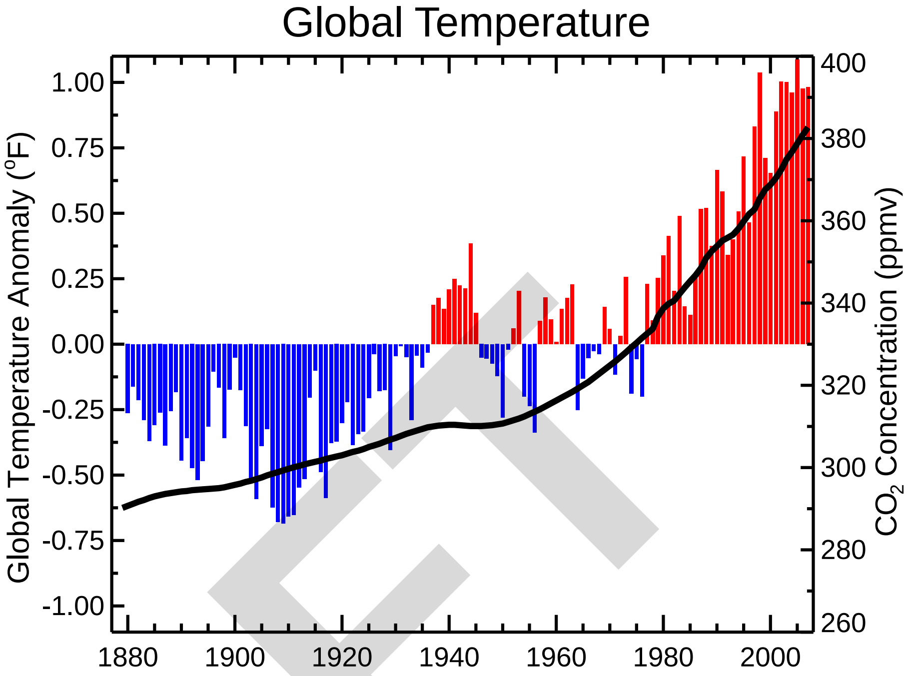
The rise in global emissions of carbon dioxide has been accelerating, with the growth rate increasing from 1.3 percent per year in the 1990s to 3.3 percent per year between 2000 and 2006[5]. This recent growth rate and the total emissions are higher than the highest emissions scenario developed by the Intergovernmental Panel on Climate Change for use in models that project future climate change.

While emissions are increasing, the rate of uptake of carbon dioxide by the oceans and vegetation on land appears to be decreasing in recent years. Both of these factors are contributing to an increased amount of carbon dioxide remaining in the atmosphere, thus raising atmospheric concentrations faster than before. Model simulations suggest that land and ocean carbon dioxide sinks would become less efficient as climate warms, but the magnitude of the observed reduction is larger than that projected by the models[6].

Temperature, precipitation and some extreme weather events have increased over the past century.

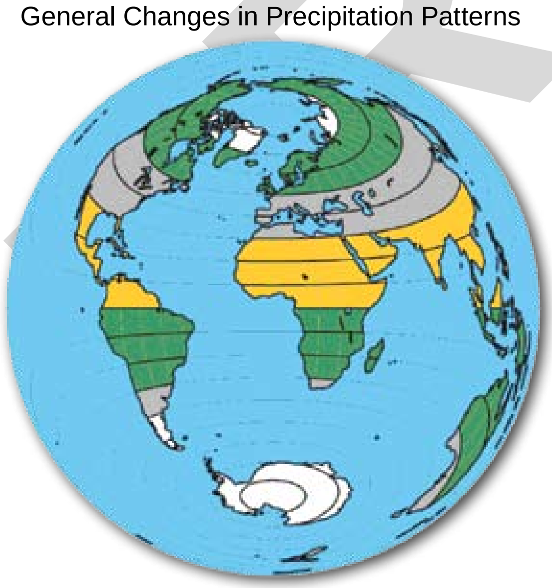
Temperatures are rising

Global average surface air temperature has been increasing, with the warming trend accelerating in recent decades. The record of temperature measurements comes from thousands of weather stations, ships, and buoys around the world; these measurements are independently compiled, analyzed, and processed by several different research groups. The warming trend that is apparent in all of these temperature records is confirmed by other observations such as the melting of Arctic sea ice, retreating mountain glaciers on every continent, earlier blooming of plants in spring, and increased melting of the polar ice sheets[7].



Global average temperature (as measured over both land and oceans) difference from twentieth century average. Red bars indicate above-average temperatures. Black line shows carbon dioxide concentrations.

Additionally, temperature measurements above the surface have been made by weather balloons since the late 1940s, and from satellite observations since 1979. These measurements show warming of the troposphere (the layer of the atmosphere just above the surface), consistent with the surface warming. They also reveal cooling in the stratosphere (the layer above the troposphere)[8]. This pattern of tropospheric warming and stratospheric cooling is consistent with our understanding of how atmospheric temperature should be changing in response to increasing greenhouse gas concentrations[9].



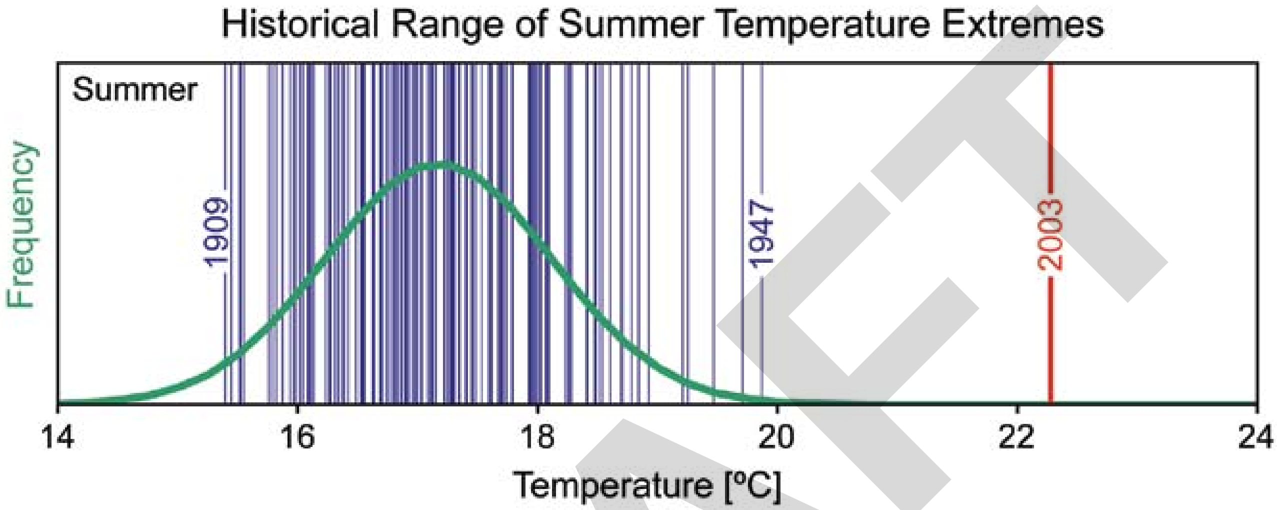
Broad scale patterns of precipitation change from 1925 to1999 show areas of increasing precipitation trends in green and decreasing trends in yellow. Areas in gray are mixed or uncertain[39].

Precipitation patterns are changing

Observations show that changes are occurring in the amount, intensity, frequency, and type of precipitation. Pronounced increases in precipitation over the past 100 years have been observed in eastern North America, southern South America, and northern Europe. Decreases were observed in the Mediterranean, most of Africa, and southern Asia (see figure at left). As the world warms, northern regions are experiencing more precipitation falling as rain rather than snow. Widespread increases in heavy precipitation events have occurred, even in places where total amounts have decreased. These changes are associated with the fact that warmer air holds more water vapor evaporating from the world's oceans and land surface. Increases in drought are not uniform, and some regions have seen increases in the occurrences of both droughts and floods[10].

Some extreme events are increasing

Over the past 50 years, the number of heatwaves has increased, as has the number of very warm nights. The extent of regions affected by droughts has also increased due to the combined effects of a small precipitation decrease over land and an increase in evaporation. Heavy precipitation events that lead to flooding have increased over many regions. Evidence suggests that there have been increases in the intensity of tropical storms and hurricanes since the 1970s[11,12].



In addition to becoming more frequent, heatwaves are also becoming more intense. For example, the temperature during the European summer of 2003 was far above the range of historical temperatures. Each vertical line on the graph above represents the average summer temperature for a single year from the average of four stations in Switzerland over the period 1864 through 2003. Temperature so far outside the historical range can have dramatic impacts, such as the enormous loss of life during that heatwave.

Global circulation patterns are changing

One reason for the variations of changes in temperature and precipitation over the globe is that as the world warms, the atmospheric circulation changes as well. For example, the equatorial region that experiences tropical climate is expanding four times faster than predicted; this tropical belt is now as wide as climate models suggested it would be at the end of this century[13]. Because the tropics drive much of the world's weather, this expansion is expected to cause shifts in weather patterns by pushing the jet stream and storm tracks northward[14], further drying out arid regions such as the U.S. Southwest and directing more intense storms toward the northern U.S. Some of these shifts already appear to be underway.

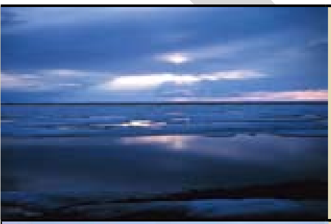
Warming is causing sea level to rise as land-based ice melts and the oceans expand.

After about 2000 years of little change, sea level rose about 8 inches over the past 100 years and is currently rising at an increasing rate. Global warming causes sea level to rise in two ways. As ocean water warms, it expands, taking up more space. In addition, the melting of glaciers and ice sheets due to warming adds water to the oceans.

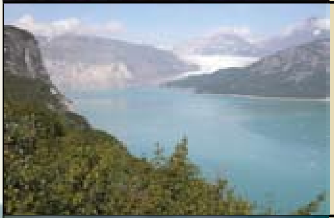
Glaciers have been retreating worldwide, especially since 1980, and at an increasing rate in the past decade[15]. While a few glaciers are not retreating (in locations where increased precipitation has outpaced melting), the vast majority of glaciers are in strong retreat, and the total volume of glaciers on Earth is declining sharply. This has major implications for water supplies in some regions and for sea-level rise globally.

The Earth has two major ice sheets: the Greenland Ice Sheet, near the north pole, which contains enough water to raise sea level by about 20 feet, and the Antarctic Ice Sheet, near the South Pole, which holds enough to raise sea levels over 200 feet. Both of these ice sheets are currently melting around some of their edges and losing ice mass at increasing rates. The Greenland Ice Sheet has also been experiencing record amounts of surface melting in recent years. Studies suggest that the surface melt water is flowing down to the base of the ice sheet, providing lubrication that causes the ice to flow more easily to the sea, speeding the loss of ice. The most recent studies of West Antarctic Ice Sheet melting show very large increases in the rate of mass loss in the past decade[16].

An Ice Primer

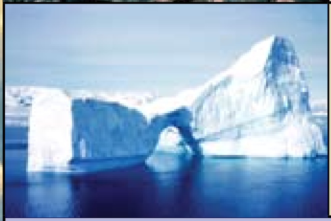


Sea Ice is formed as ocean water freezes. It is less dense than water, so it floats on top of the ocean. As sea ice forms, it rejects most of its salt to the surrounding ocean.



Glaciers and Ice Caps are land-based ice, with ice caps topping hills and mountains, and glaciers filling the valleys, although the term glacier is often used to refer to both ice caps and glaciers.

An **Ice Sheet** is a collection of ice caps and glaciers that form one large mass, such as currently found on Greenland and Antarctica.

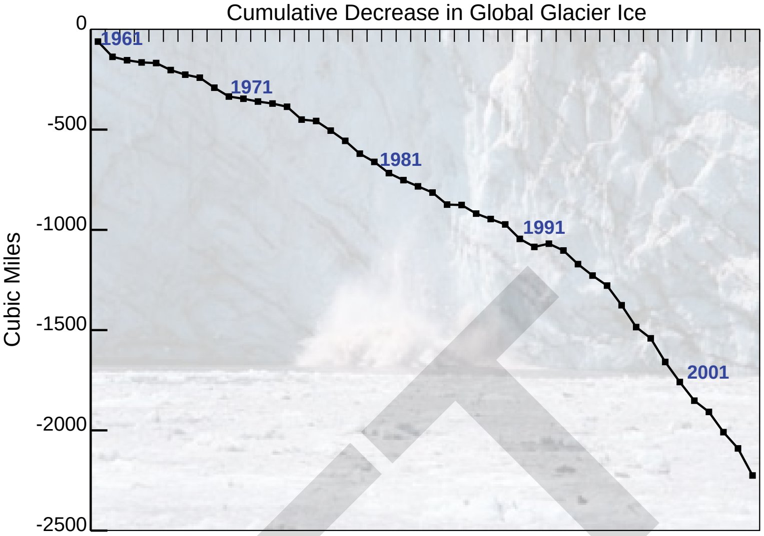


An **Iceberg** is a chunk of ice that breaks off of a glacier, ice sheet, or **ice shelf** (an extension of ice from land out on the ocean) and floats on the ocean's surface.

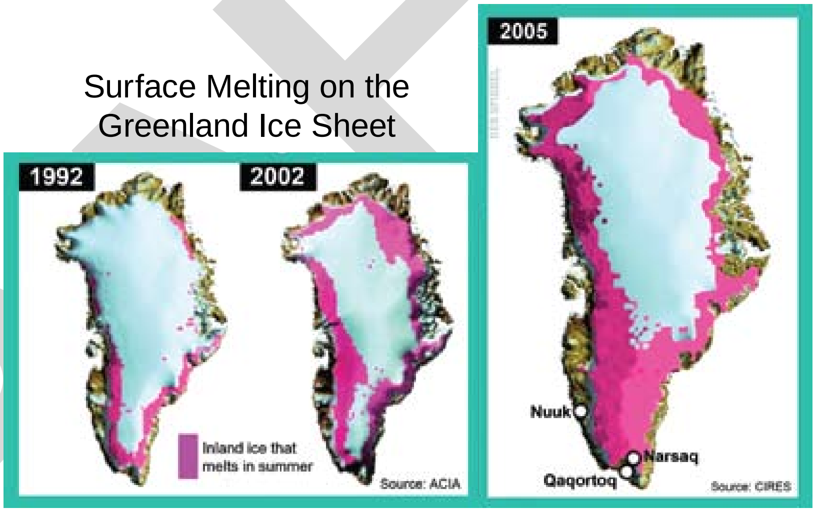
When glaciers, ice caps, and ice sheets melt, they cause sea level to rise by adding to the amount of water in the oceans. Melting sea ice and ice shelves do not cause sea level to rise.

In addition to land-based ice like glaciers and ice sheets, the polar regions also have ice on the surface of their oceans. The amount of this sea ice varies with the seasons, growing more extensive in winter and melting back in summer.

Earth's two poles are responding differently to human influences on climate for several reasons. The northern polar region, known as the Arctic, is warming very rapidly across the region. In Antarctica, the cooling influence of stratospheric ozone depletion over the South Pole is likely to be masking the effect of global warming. In addition, the temperatures are so cold in Antarctica, initial warming does not necessarily lead to melting of snow and ice. The slightly increasing trend in Antarctic sea ice over the past 30 years is also likely to have been influenced by the way stratospheric ozone depletion has affected atmospheric circulation: westerly winds have increased by an average of 15 percent across the Southern Ocean and Antarctica, effectively blocking warmer air from reaching the continent. This phenomenon has not affected the area around the West Antarctic Peninsula, which has experienced significant reductions in sea ice consistent with the strong warming in that region.



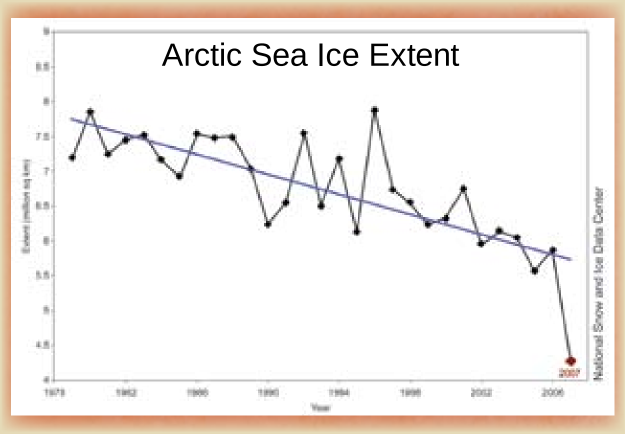
(see endnote 40)



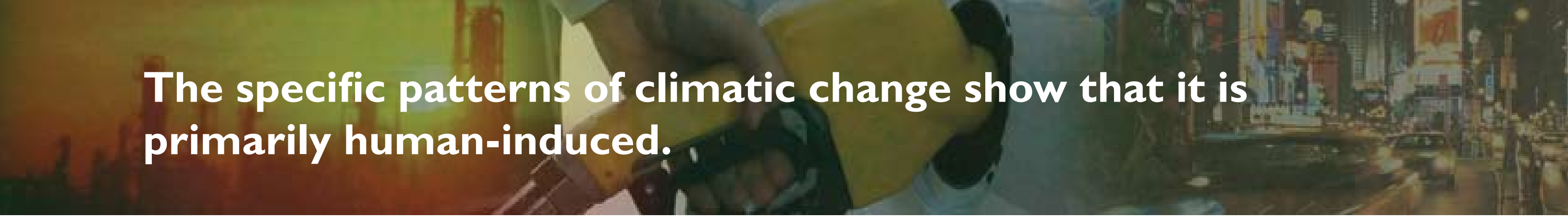
Surface Melting on the Greenland Ice Sheet

Arctic sea ice decline is accelerating

In the northern polar region, the sea ice on the Arctic Ocean has been declining for the last three decades, with declines in both thickness and extent becoming quite dramatic in recent years. Sea ice is a very important part of the climate system, affecting surface reflectivity, cloudiness, humidity, exchanges of heat and moisture at the ocean's surface, and ocean currents. For example, melting of sea ice makes the ocean surface darker, which allows it to absorb more of the Sun's heat, which increases warming. As in the case of warming increasing water vapor, this is another example of a "feedback loop." Changes in sea ice have enormous environmental, economic, and societal implications[17].



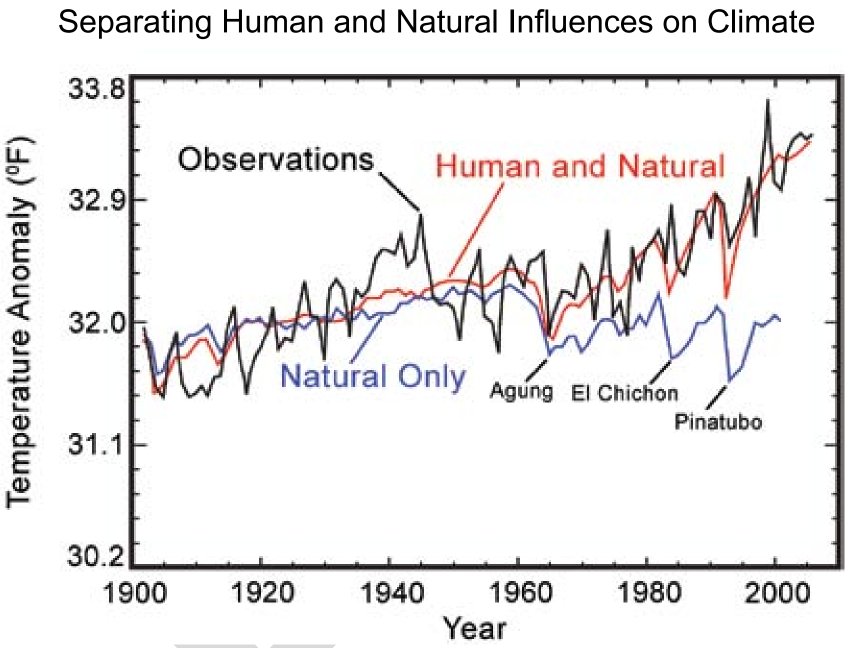
Arctic sea ice extent in September (the annual minimum) since satellite observations began.



The specific patterns of climatic change show that it is primarily human-induced.

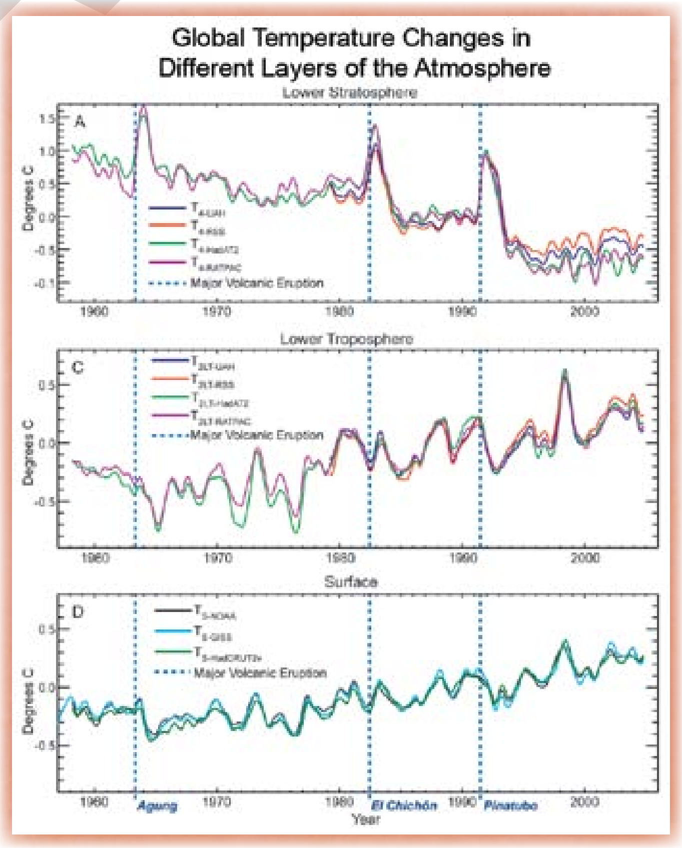
Each factor that affects climate produces a unique pattern of climate response, much as each person has a unique fingerprint. We can thus use detailed pattern analyses called fingerprint studies to determine cause and effect relationships in the climate system. Climate scientists rely on such studies to attribute observed changes in climate to particular causes. Each fingerprint study includes estimates of the natural variations (or "noise") in climate, and tests whether these natural variations could explain the observed climate changes.

Attribution studies generally involve comparing observed changes with simulations from climate models in which specific factors are varied. The benefit of using models in this way is that we can do what we can't do in the real world: add and remove particular factors and see how climate responds to these factors individually and together[18].


Separating Human and Natural Influences on Climate

The blue line shows how global average temperatures would have changed due to natural forces only. The red line shows the effect of human and natural forces as simulated by climate models. The black line shows actual observed global average temperatures. As the blue line indicates, without human influences, temperature over the past century would actually have first warmed and then cooled slightly.

For example, climate model simulations of the last century that include all of the major influences on climate, both human-induced and natural, reproduce many important features of observed climate change patterns. When the human influences are removed from the models, the result shows that climate would actually have first warmed and then cooled slightly over the last century. The clear message from fingerprint studies is that the observed warming could not have been caused by natural factors alone[19].


Global Temperature Changes in Different Layers of the Atmosphere

Similarly, the pattern of temperature changes vertically through the layers of the atmosphere, from the surface up through the stratosphere, indicates that the most likely cause of the warming is the human-induced build-up of heat-trapping gases. All climate models show that heat-trapping greenhouse gases cause warming at the surface and in the layer just above the surface (the troposphere) but lead to cooling in the stratosphere. The observed pattern of climate change matches the model fingerprint, and also shows warming of the troposphere and cooling of the stratosphere. If most of the observed surface and tropospheric warming

had been caused by an increase in solar output rather than by greenhouse gases, we should have observed warming throughout most of the atmosphere, including the stratosphere[20]. Observed climate change is therefore inconsistent with the hypothesis that changes in the Sun can explain the warming of recent decades.

Other fingerprint analyses have looked at changes in the heat content of the oceans, the height of the tropopause (the boundary between the troposphere and stratosphere, which has shifted upward by hundreds of feet in recent decades), the geographic redistribution of precipitation, surface pressure patterns, the humidity close to Earth's surface, and the moisture content of the atmosphere over the oceans. Fingerprint studies have also been used to analyze how much human-induced warming has increased the risk of occurrence of certain types of extreme weather events. For example, an analysis of the European summer heat wave of 2003 found that the risk of such a heat wave is now roughly four times as great due to human influences on climate[21].

On the question of hurricanes, analyses have found a strong correlation between sea surface temperatures and hurricane power, with both showing increasing trends in the Atlantic in recent decades. Observations indicate that sea surface temperatures have increased in the regions of the Atlantic and Pacific where hurricanes are born. Fingerprint analysis used to determine the cause of the increased ocean temperature in these key regions found that most of the increase was due to human influences and not natural variations. The authors concluded that the human-induced increase in heat-trapping gases was the main driver of the rise in sea surface temperatures in these key ocean regions[23].

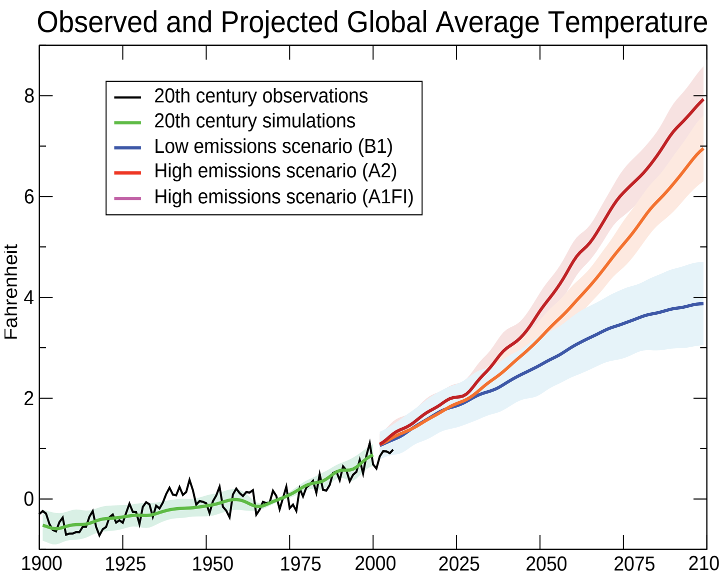
The fingerprint studies described above analyze different climatic variables. Each study has concluded that human influences are the primary driver of recent climatic changes, and that natural factors cannot account for these changes. All of the observed changes are consistent with each other and with our scientific understanding of how the climate system should be responding to the increase in heat-trapping gases resulting from human activities[24].

Graphic under development

Climate will warm more in the future; how much depends on the level of emissions and how sensitive the climate will be to those emissions.

Rising global temperature

All climate models project that human-caused emissions of heat-trapping gases will cause further warming in the future, with global average temperature projected to rise by 3 to 11.5°F by the end of this century. About 1.5°F of this total warming has already occurred over the past century, so the additional warming would be in the range of 1.5 to 10°F above today's level. Whether the warming will be nearer the low or the high end of this range depends on two factors: first, the future level of emissions of heat-trapping gases, and second, how sensitive climate will be, that is, how much climate will change in response to those emissions. The range of possible outcomes has been explored using a range of different emissions scenarios, and a variety of climate models, each with a different sensitivity.

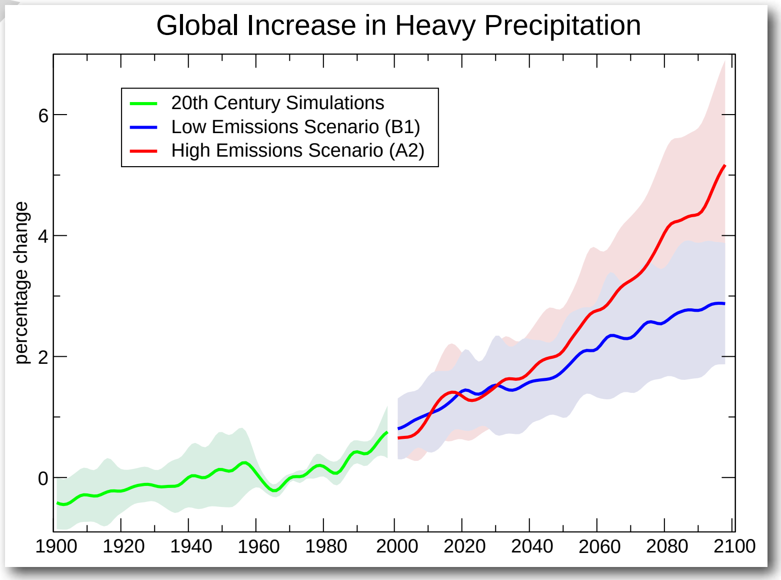


Observed and projected changes in the global average temperature under three emissions scenarios. The shaded areas show the possible ranges while the lines show the central projections from a set of climate models.

The IPCC developed a set of scenarios in a Special Report on Emissions Scenarios (SRES)[25]. These have been extensively analyzed by scientists to understand future climate change. None of these scenarios include explicit policies to limit climate change. Rather, emissions in these scenarios vary based on different assumptions about changes in population, adoption of new technologies, economic growth, and other factors. None of them involve stabilizing atmospheric concentrations of heat-trapping gases at a level that would avoid dangerous human interference with the climate system as required by the Framework Convention on Climate Change.

Changing precipitation patterns

Projections of future changes in precipitation largely follow recently observed patterns of change, with overall increases in the global average but substantial shifts in where and how precipitation falls. Generally, higher latitudes are projected to become wetter while the sub-tropics become drier. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), and especially over the tropical Pacific. Certain regions, including the U.S. West and Southwest and the Mediterranean, are expected to become drier. The trend towards more heavy downpours is expected to continue, with precipitation becoming less frequent but more intense[26]. More precipitation is expected to fall as rain rather than snow.



Observed and projected changes in the heaviest 5 percent of precipitation events. The shaded areas show the possible ranges while the lines show the central projections from a set of climate models.

Currently rare extreme events become more common

In a warmer future climate, there will be an increased risk of more intense, more frequent and longer-lasting heat waves. The European heat wave of 2003 is an example of the type of extreme heat event that is likely to become more common[27], with the likelihood of such a heat wave projected to increase 100-fold in the next 40 years. If greenhouse gas emissions continue to increase as projected, by the 2040s more than half of European summers will be hotter than the summer of 2003, and by the end of this century, a summer as hot as that of 2003 will be considered unusually cool[28].

Increased extremes of summer dryness and winter wetness are projected for much of the globe, meaning a generally greater risk of droughts and floods. This has already been observed and is projected to continue, because in a warmer world, precipitation tends to be concentrated into more intense events, with longer periods of little precipitation in between. Therefore, heavy downpours would be interspersed with longer relatively dry periods[29].

Models project a general tendency for more intense but fewer storms overall outside the tropics, with more extreme wind events and higher ocean waves in several regions in association with those storms. Models also project a shift of storm tracks toward the poles in both hemispheres[30].

Changes in hurricanes are difficult to project because there are countervailing forces. Higher ocean temperatures lead to stronger storms with higher wind speeds and more rainfall. But changes in wind speed and direction with height are also projected to increase in some regions, and this tends to work against storm formation and growth. It currently appears that stronger tropical storms and hurricanes are likely in some regions, though more research is required on these issues.

Sea level will continue to rise

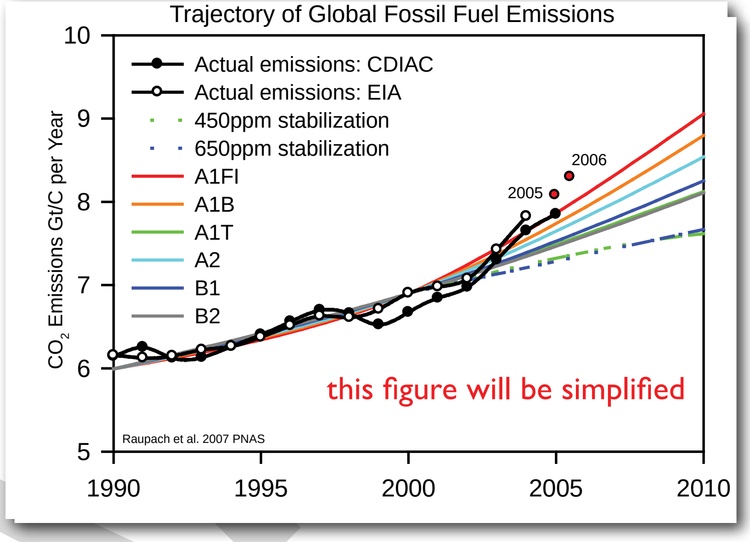
Projecting future sea-level rise presents special challenges. Scientists have a well-developed understanding of the contributions of thermal expansion and glacier-melt to sea-level rise, so the models used to project sea-level rise include these processes. However, recent observations on Greenland and Antarctica show that additional processes are at work which affect the dynamic responses of ice sheets to warming. Although these processes are not yet well understood or included in current climate models, they are probably already producing substantial additional loss of ice mass and are thus contributing to sea-level rise (see further discussion under "Abrupt climate change" on next page).

Thus, most current models can give us only a lower bound for future sea-level rise projections, with a highly uncertain upper bound. The 2007 assessment by the Intergovernmental Panel on Climate Change set the range of this lower bound at about two thirds of a foot to 2 feet of sea-level rise by the end of this century. Various methods of estimating future sea-level rise suggest increases of 2 to almost 5 feet by the end of this century, but even larger numbers cannot be ruled out.

The human effect on climate can be minimized if emissions are sharply reduced.

The scenarios described on the previous page do not encompass the full range of possible futures: climate can change less than those scenarios imply, or it can change more. Current carbon dioxide emissions are, in fact, above the highest emissions scenario developed by the Intergovernmental Panel on Climate Change (IPCC), implying that if we stay the current course, we're heading for even larger warming than the highest projections from the IPCC.

There are also lower possible emissions paths than those put forth by the IPCC. The Framework Convention on Climate Change, to which the United States and most other countries are signatories, calls for stabilizing concentrations of greenhouse gases in the atmosphere at a level that would avoid dangerous human interference with the climate system. What exactly constitutes such interference is subject to interpretation. Some argue, based on a number of criteria, including already observed impacts, that we have already crossed into "dangerous" territory and that what we must now seek to avoid is catastrophic climate change.



Raupach et al. 2007 PNAS

this figure will be simplified

Given that global temperature has already risen 1.5°F above pre-industrial levels and significant impacts are already apparent, it has been suggested that avoiding more severe, widespread, and irreversible impacts would require limiting the total temperature rise to no more than 3.5°F above pre industrial levels. To have a good chance (but not a guarantee) of avoiding temperatures above those levels, it has been estimated that atmospheric concentrations of carbon dioxide would need to stabilize in the long-term at around today's levels. There is not one precise number for the carbon dioxide "stabilization target" because the sensitivity of the climate system to greenhouse gases is not known precisely; different models show different temperature changes for the same stabilization target.

A further complication is that carbon dioxide is not the only greenhouse gas of concern. Concentrations of other greenhouse gases like methane and nitrous oxide would also have to be stabilized at low enough levels to prevent global temperatures from rising above the level mentioned above. When these other gases are added, including the offsetting cooling effects of certain aerosol particles, analyses suggest that stabilizing concentrations around 400 parts per million of CO$_2$ would yield about an 80 percent chance of avoiding exceeding the 3.5°F threshold. This would be true even if concentrations temporarily peaked as high as 475 parts per million and then stabilized at 400 roughly a century later[33,34,35,36,37.]

Climate can also change abruptly, as is evident from ice core records of past climate.

Figure under development

Abrupt climate change

At the other end of the spectrum is the possibility of even larger climate change than current scenarios and models project, including possible abrupt climate change. Not all climate changes are gradual. The long record of climate found in ice cores, tree rings, and other natural records show that Earth's climate has undergone abrupt shifts from one stable state to another. Such changes occur so rapidly that they would challenge the ability of human and natural systems to adapt. Examples of such changes are abrupt shifts in drought frequency and duration. Ancient climate records suggest that in the U.S., the Southwest may be at greatest risk for this kind of change, but that other regions including the Midwest and Great Plains have also had these kinds of abrupt shifts in the past and could experience them in the future.

Small grains of sand ground out by glaciers and carried far out across the North Atlantic by icebergs, deposited over intervals from a few decades to a few centuries, provide evidence that the Northern ice sheets have melted abruptly in the past (Photo credit: J. Andrews, U. of Colorado)

Rapid ice sheet collapse and related sea-level rise is another type of abrupt change that is not well understood or modeled and poses a risk for the future. Recent observations show that melting on the surface of an ice sheet produces water that flows down through large cracks that create conduits through the ice to the base of the ice sheet where it lubricates ice previously frozen to the rock below. Further, the interaction with warm ocean water where ice meets the sea, this can lead to sudden losses in ice mass and accompanying rapid global sea-level rise. Observations indicate that ice loss has increased dramatically over the last decade, though scientists are not yet confident that they can project how the ice sheets will respond in the future. Recent studies suggest that sea level could rise as much as 3 to 5 feet per century over the next several centuries[32].

National Climate Change

Temperature

- U.S. temperatures are rising.
- They are projected to rise much more in this century.
- Just how much more depends primarily on the amount of heat-trapping emissions.

Precipitation

- Precipitation has generally been increasing, but not in all areas.
- Dry areas are generally expected to become drier while wet areas become wetter.
- More precipitation has been occurring in heavy downpours.
- Precipitation is projected to continue recent trends, becoming less frequent (longer periods between events) but more intense.

Storms

- Atlantic hurricanes have increased in intensity. There has been no overall change in the frequency of land-falling hurricanes.
- The most intense storms are likely to become even stronger, with greater wind speed and rain fall rates.
- Storm tracks have been shifting northward in the U.S., and are projected to continue to do so.
- Cold-season storms are projected to become stronger in the most northerly locations.

Extreme weather

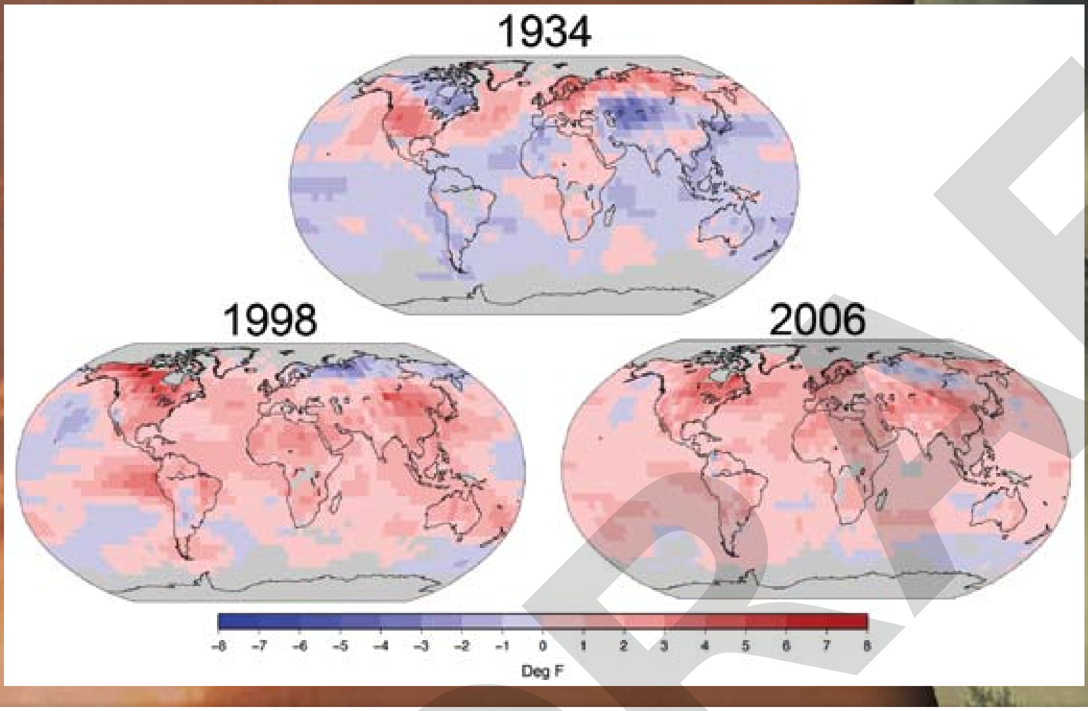
- Heatwaves and heavy downpours are becoming more frequent and more intense and this is projected to continue.

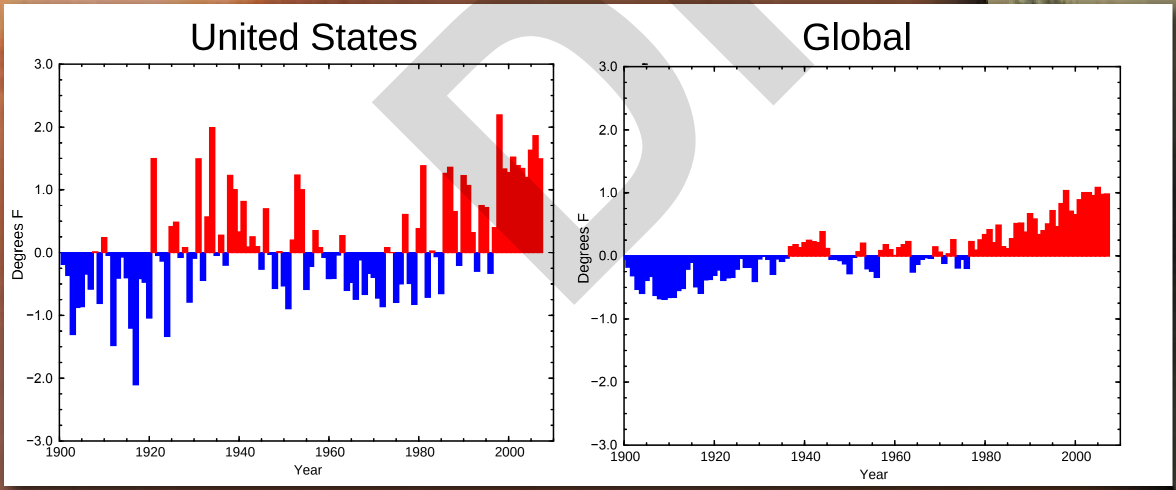
Emissions

- U.S. emissions of heat-trapping gases are rising and come primary from burning fossil fuels.
- Uptake of carbon by trees in the United States absorbs about one-third of our emissions. Another one-third is absorbed by the oceans and vegetation in other regions.
- The remaining one-third accumulates in the atmosphere, adding to the greenhouse effect, leading to further global climate change.

Like the rest of the world, the United States has been warming significantly over the past 50 years in response to the build up of heat-trapping gases. When looking at national climate, however, it is important to recognize that climate varies much more at the scale of a country than at the scale of the globe. While various parts of the world have had particularly hot or cold periods in earlier parts in the historical record, these periods have *not* been global in scale, whereas the warming of recent decades has been truly global – hence the term *global* warming.

For example, the 1930s were very warm in much of the United States, but they were *not* unusually warm globally. On the other hand, the warmth of recent decades has been global in extent. The maps show annual average temperatures across the globe for the three years that were the hottest three on record in the United States: 1998, 1934 and 2006.





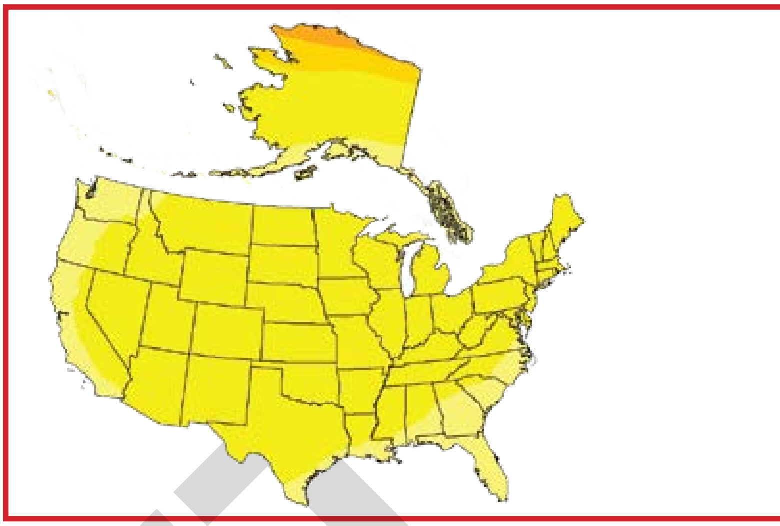
Annual average temperatures compared to mean baseline.

U.S. Temperatures

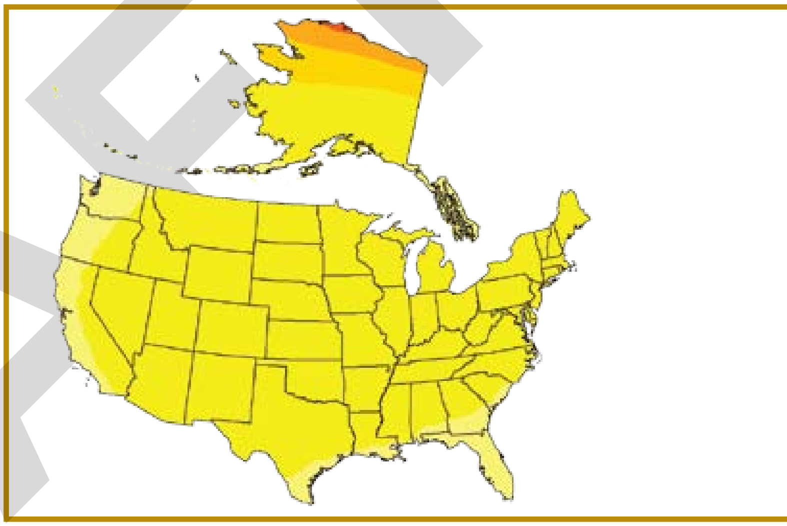
2020

Projected Change in Annual Average Temperature

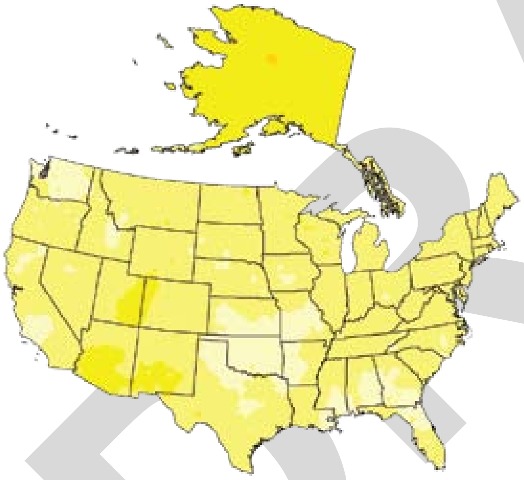
High Emissions*

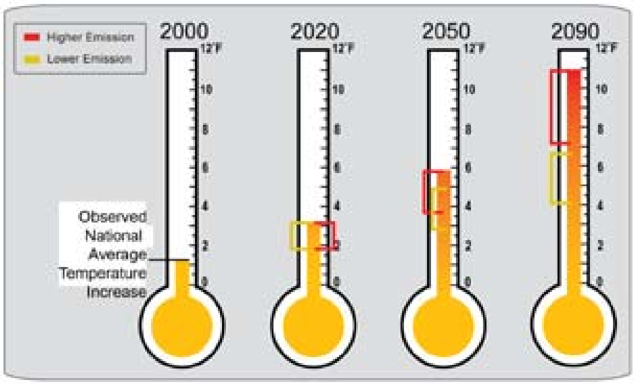


Low Emissions*



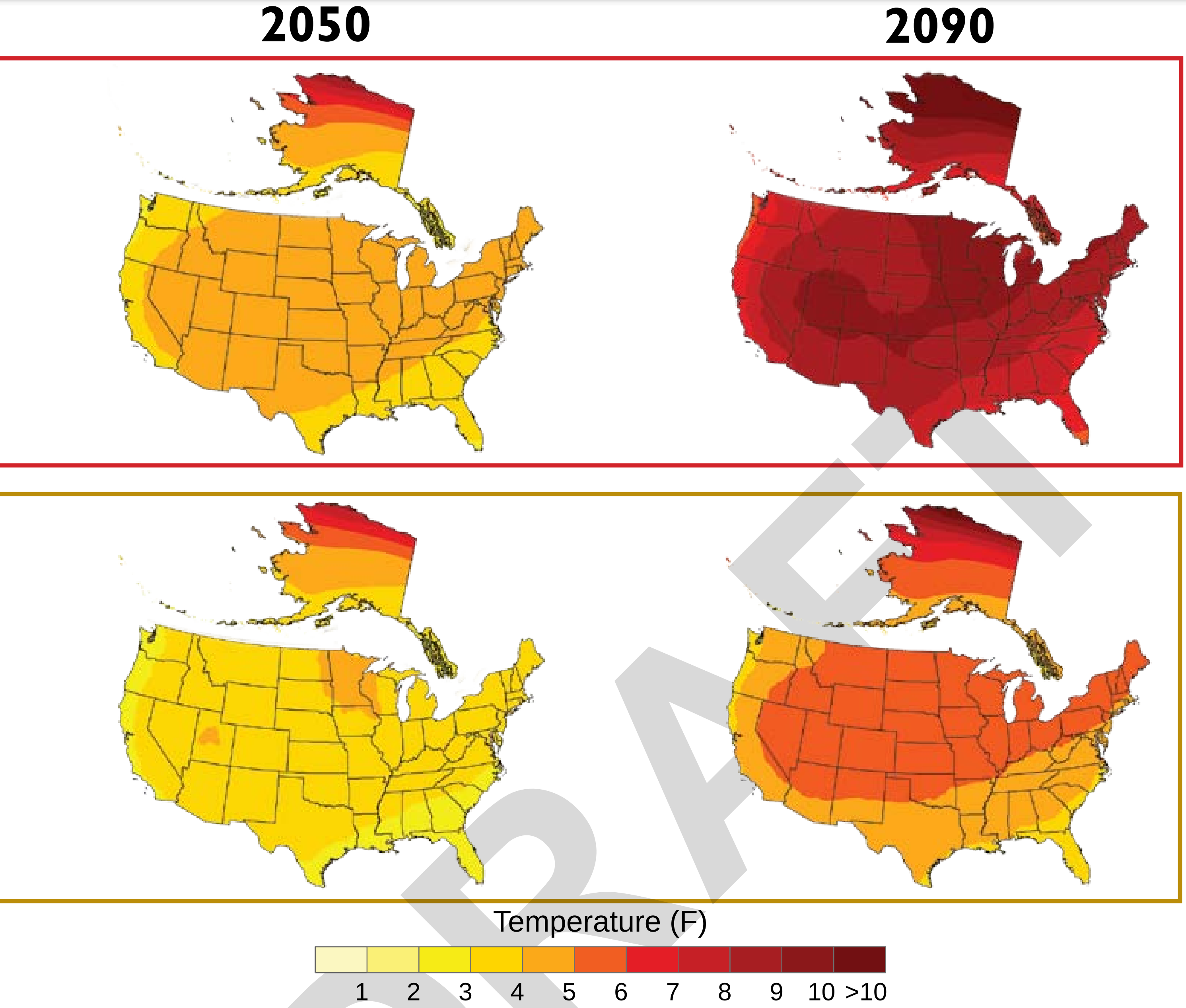
Observed Change in Annual Average Temperature 1970-2000

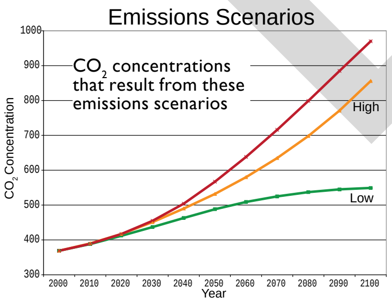




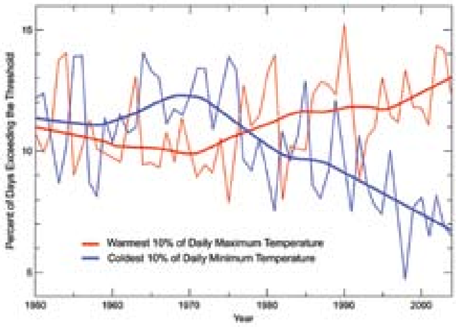
Temperatures in the U.S. have risen over the past 50 years and are projected to rise even more in this century. The first map shows observed warming since the 1960s and the remaining six maps show projected annual average warming over the course of this century under a low emissions and a high emissions scenario.

Temperature increases in the next couple of decades will be primarily determined by past emissions of heat-trapping gases. This explains why there is little difference between the maps showing the two scenarios for 2020. Increases after the next couple of decades will be primarily determined by future emissions, as seen on the maps for the middle and end of this century.





* The maps on this page are based on sixteen models' projections of future temperature using two scenarios of carbon dioxide emissions from the Intergovernmental Panel on Climate Change (IPCC), Special Report on Emission Scenarios (SRES)[1]. The "low" scenario here is IPCC SRES B1, while the "high" is A2. In other places in this report, the higher scenario A1FI (red line in graphic at left) is used as the "high" scenario.



As average temperature has increased, cold extremes have decreased and hot extremes have increased, as shown on the chart above.

U.S. Precipitation

Precipitation over the United States as a whole has generally increased, though there have been important regional differences. Wetter areas, such as the Northeast, have generally become wetter while drier areas, such as the Southwest, have generally become drier. This fits the pattern projected to occur due to warming. There have also been seasonal differences, with some seasons showing large increases or decreases in various regions.

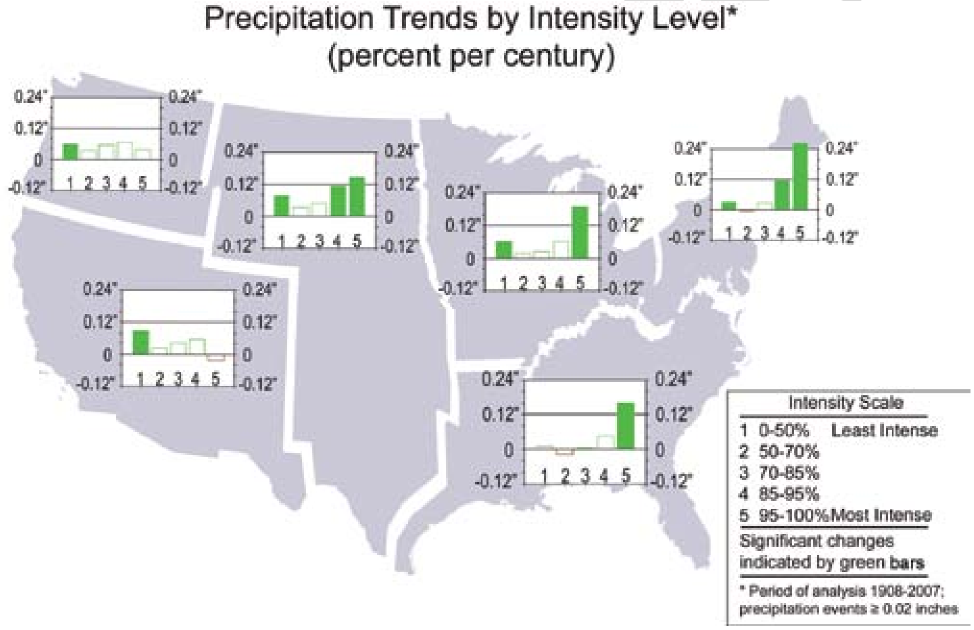
One of the clearest precipitation trends in the U.S. is the increasing frequency and intensity of heavy downpours. The amount of precipitation falling in the heaviest 1 percent of rain events increased nearly 20 percent over the past century. Total average precipitation over the nation as a whole increased by about 7 percent, with individual locations ranging from much more to much less than this average.[2]

Model projections of future precipitation generally suggest continuations of observed patterns, with northern areas becoming wetter and southern areas, particular in the West, becoming drier.

Precipitation changes due to human-induced warming are more difficult to predict than changes in temperature. It is virtually certain that in some seasons, some areas will experience an increase in precipitation, other areas experience a decrease, and others will see little discernible change. The difficulty arises in predicting the extent of those areas and the amount of change.

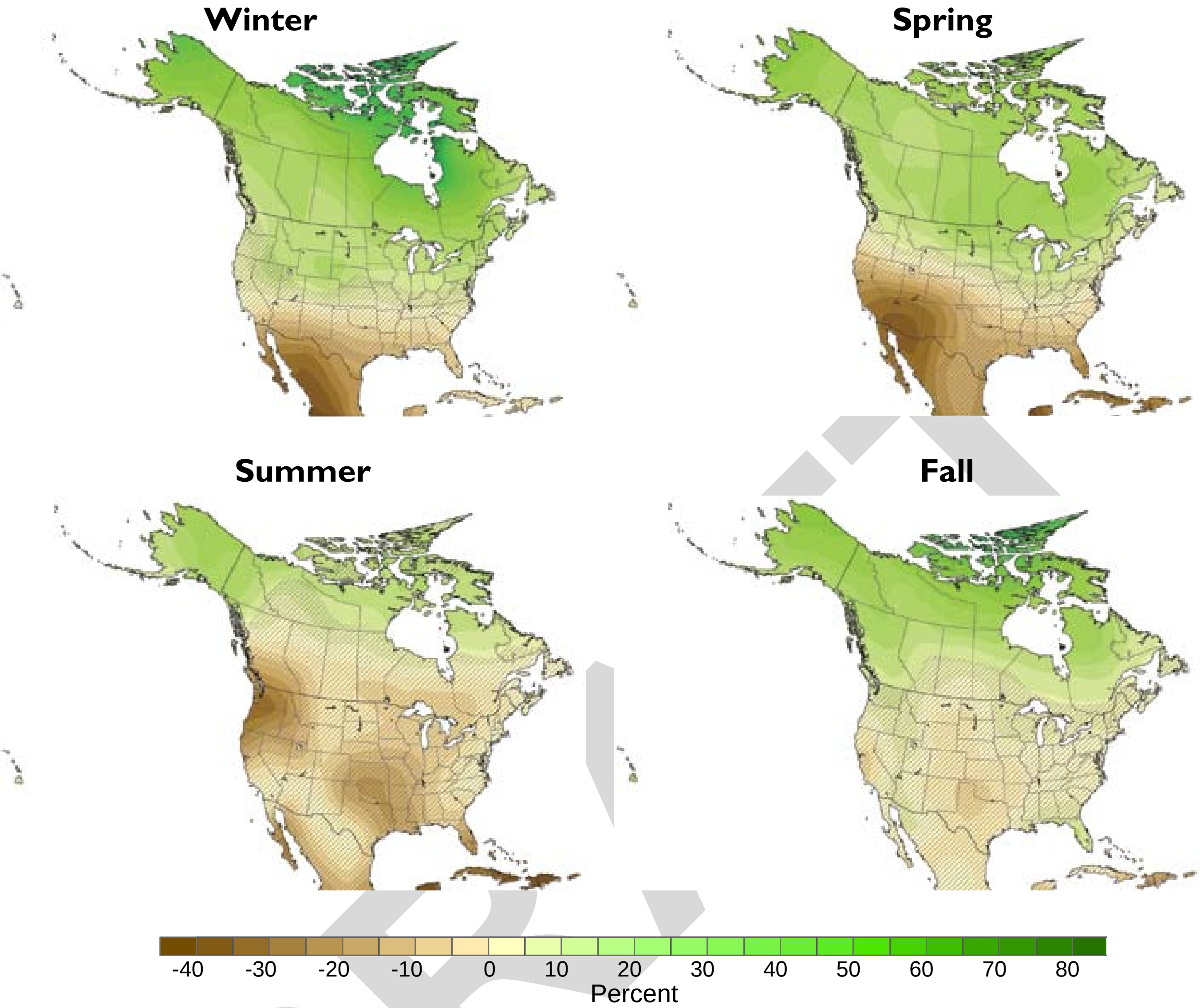
The maps to the right show the best estimates of percentage changes in seasonal average precipitation by the end of this century in a high emissions scenario based on 15 climate models. The hatched areas are less certain than unhatched. Confidence in predicted changes are higher in winter and spring than in summer and fall.

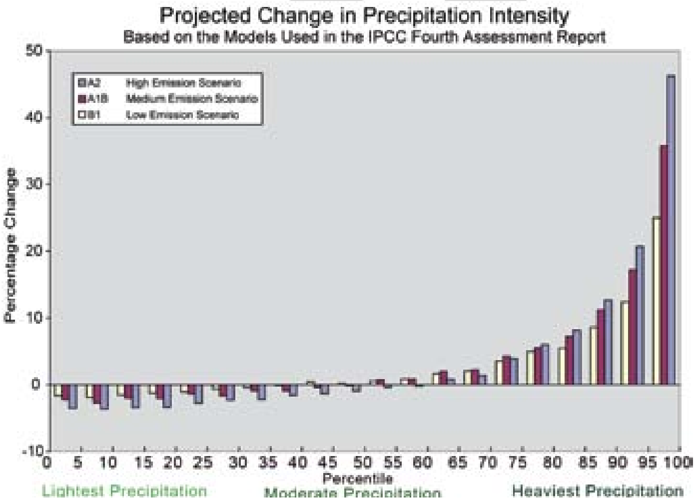
In winter and spring, northern areas are expected to receive significantly more precipitation than they do now, because warmer air holds more moisture. This effect is particularly noticeable in northern regions that will go from very cold and dry conditions to warmer but snowier conditions. Alaska is already experiencing this and the Great Plains, upper Midwest, and Northeast are likely to experience this in the next few decades. Significant reductions in precipitation are predicted in southern areas in winter and spring. This is particularly pronounced in the Southwest, where it will have serious ramifications for water resources.



The bar graphs show trends in precipitation intensity by region. Each bar represents precipitation of a particular intensity with the far left bar being lighter rainfall and the far right bar the heaviest.

Projected Change in North American Precipitation





The maps above show model projections of precipitation changes by the end of this century in percent by seasons. Hatched area are less certain than unhatched areas.

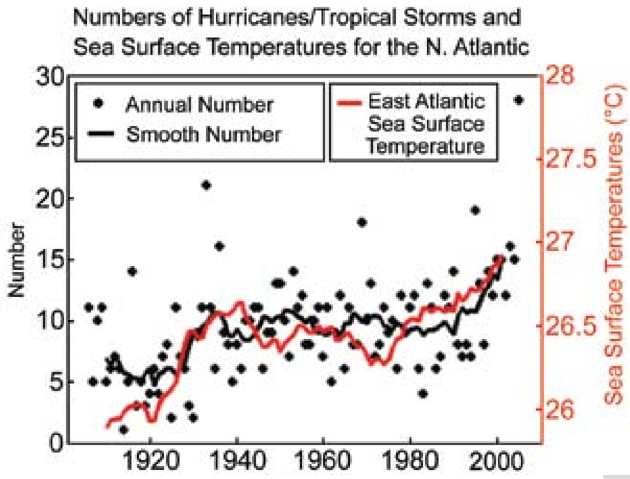
The figure to the left shows projected changes in the intensity of precipitation displayed in 5 percent increments from the lightest drizzles to the heaviest downpours. As shown here, the lightest precipitation is projected to decrease, while the heaviest will increase, continuing the observed trend. The higher emission scenarios yield larger changes.

Storms

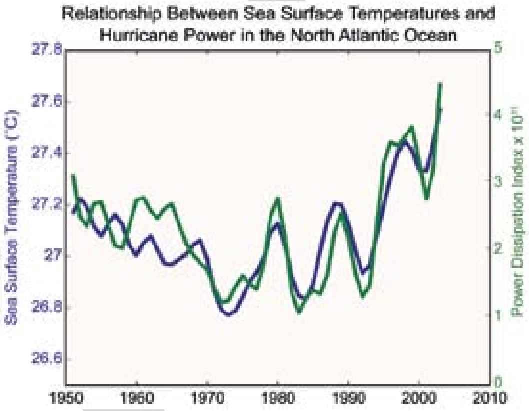
Changes in extreme weather and climate events are among the most serious challenges to our nation in coping with a changing climate. Many extremes and their associated impacts are now changing. The U.S. has been experiencing more unusually hot days and nights. Heavy downpours have become more frequent and intense. Droughts are becoming more severe in some regions. These trends are projected to continue[4].

The power and frequency of Atlantic hurricanes have increased substantially in recent decades as shown on the graphs below. In the future, the most intense hurricanes are likely to become even stronger, with greater wind speeds, rain fall rates, and storm surge levels[5].

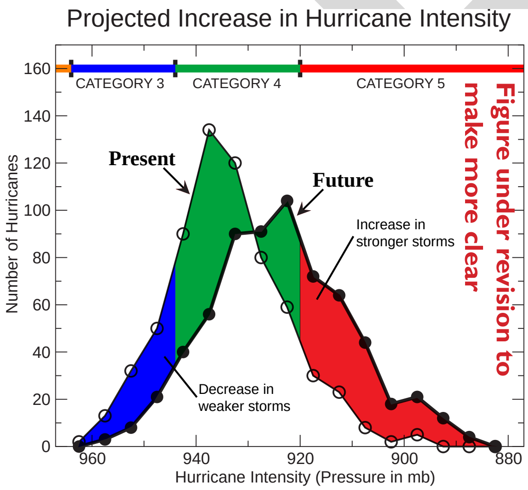
Outside the tropics, storm tracks are shifting northward and are projected to continue to do so. Strong cold season storms are likely to become stronger and more frequent, with greater wind speeds and more extreme wave heights.



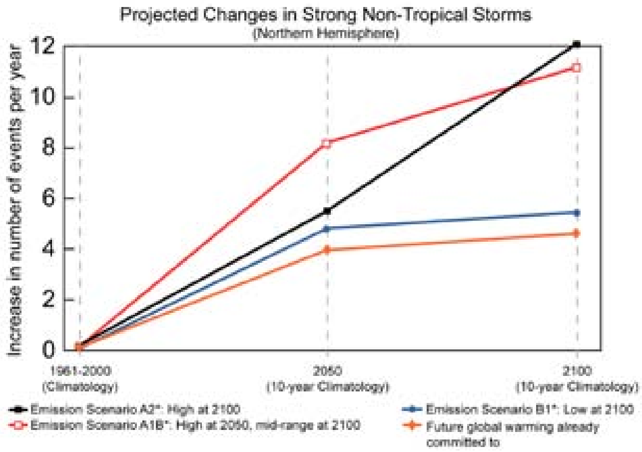
Annual numbers of hurricanes/tropical storms in the North Atlantic (black dots) and 9-year running mean (black line) are correlated with sea surface temperature (9-year smoothed temperature, red line).



Sea surface temperature (blue) and the Power Dissipation Index for North Atlantic hurricanes. Hurricane rainfall and wind speeds are likely to increase in response to human-caused warming. Analyses of model simulations suggest that for each 1.8°F increase in tropical sea surface temperatures, core rainfall rates will increase by 6-18 percent.

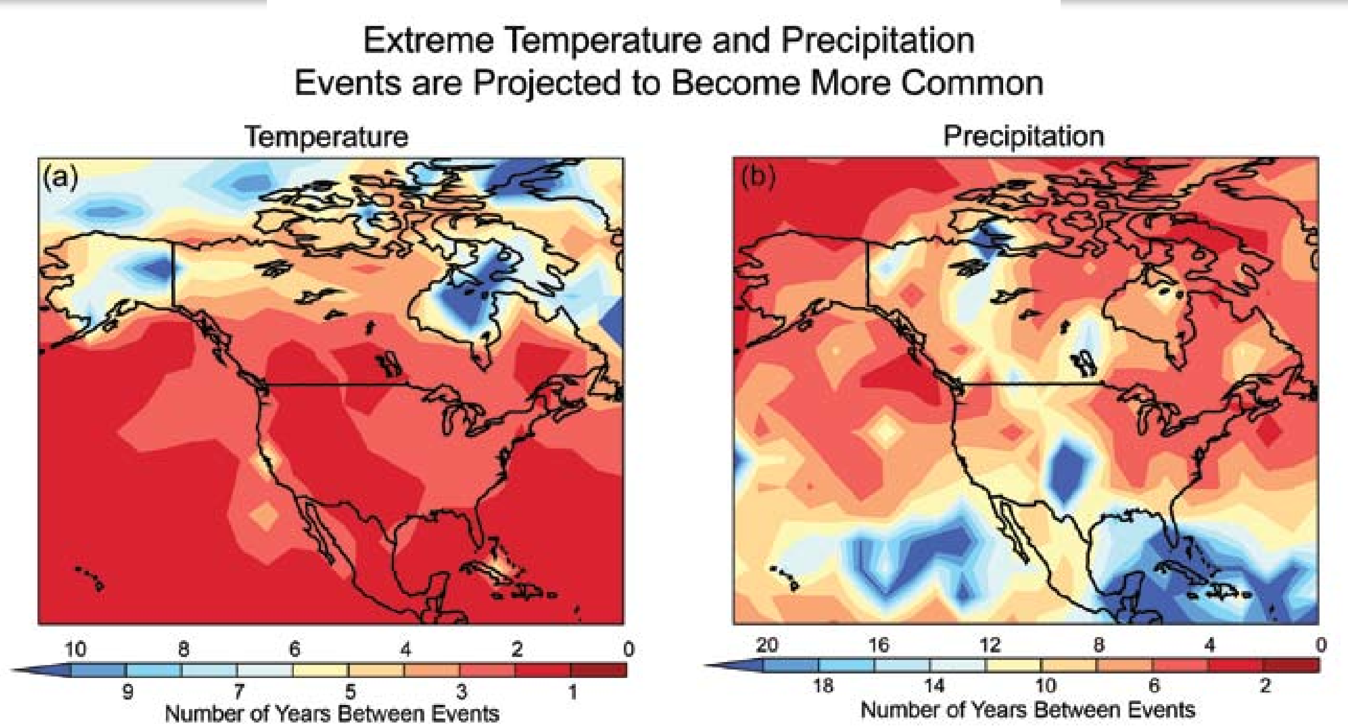


Strong hurricanes are projected to increase and weak hurricanes are projected to decrease.



The projected change in intense low pressure systems (strong storms) during the cold seasons for the Northern Hemisphere for various emission scenarios. There are likely to be more frequent deep low-pressure systems (strong storms) outside the tropics, with stronger winds and more extreme wave heights.

Extreme weather



a) Simulations for 2090-2099 indicate how currently rare extremes (a 1-in-20-year event) are projected to become more commonplace. A day so hot that it is currently experienced once every 20 years would occur every other year or more by the end of the century.

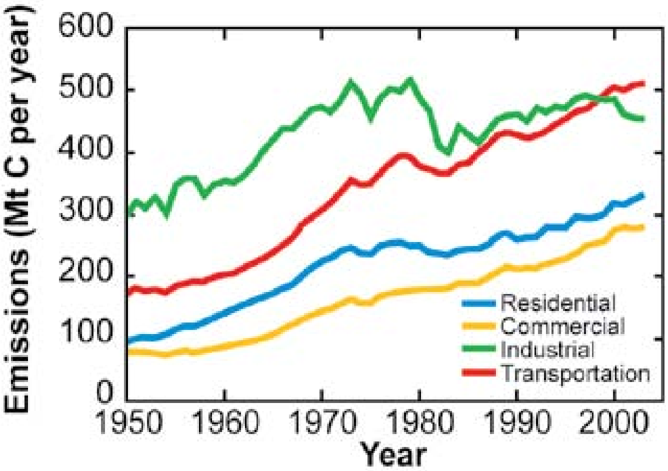
b) Daily total precipitation events that occur on average every 20 years in the present climate would, for example, occur once every 4-6 years for Northeast North America. These results are based on a multi-model ensemble of global climate models.

Extreme heatwaves that we currently consider rare will occur more frequently in the future. Hot days that are currently considered 1-in-20 year occurrences are projected to happen about every other year by the end of this century. Heavy downpours that are now 1-in-20 year occurrences are projected to occur about every 4 to 15 years by the end of this century, depending on location.

The intensity of extreme events like these will also increase in the future. For instance, a day so hot that it occurs once every twenty years at the end of the century will be as much as 11°F hotter than a day that rare at present. The once every twenty year heavy downpour is expected to be between 13 and 24 percent heavier by the end of the century than it is now.

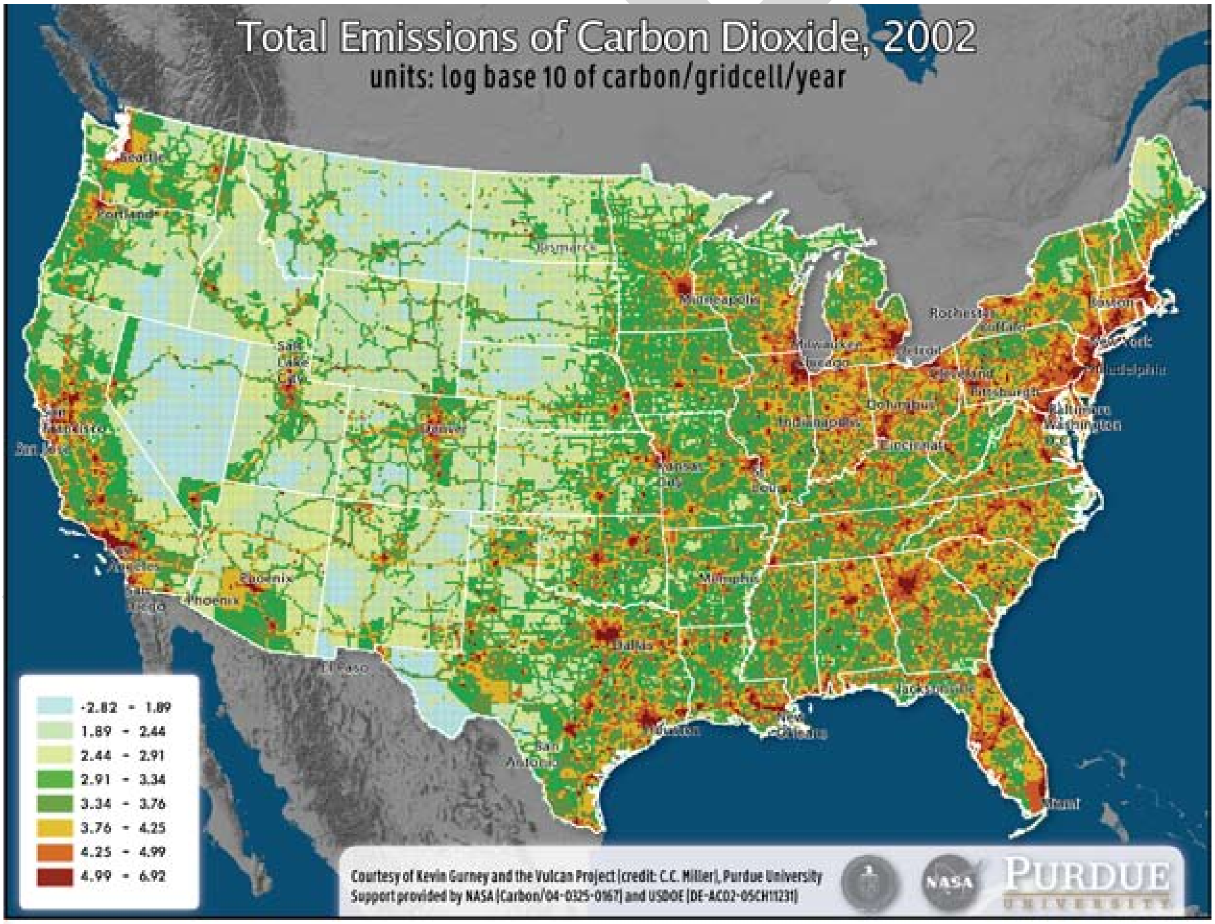
U.S. Emissions of Heat-trapping Gases

The build up of heat-trapping gases is driving global warming. Since the industrial revolution, the United States has been the world's largest emitter of those gases, though China has recently surpassed the U.S. in current emissions. Carbon dioxide, the most important of the heat-trapping gases produced directly by human activities, is a cumulative problem, because it has a long atmospheric lifetime. One third of the carbon dioxide released from fossil fuel burning remains in the atmosphere after 100 years, and one-fifth of it remains after 1000 years. As a result, the U.S. is responsible for about 28 percent of the human-induced heat-trapping gases in the atmosphere today[6].



Historical U.S. carbon emissions.

U.S. carbon dioxide emissions have been growing. These emissions are almost entirely from fossil fuels. These sources of carbon are one side of the equation, the other side of which involves "sinks" that take up carbon dioxide. In the U.S., natural sinks (primarily the growth of trees and other plants) currently take up the equivalent of about one third of our emissions. Another one-third is absorbed by the oceans and vegetation in other regions. The remaining one-third accumulates in the atmosphere, adding to the greenhouse effect, leading to further global climate change.

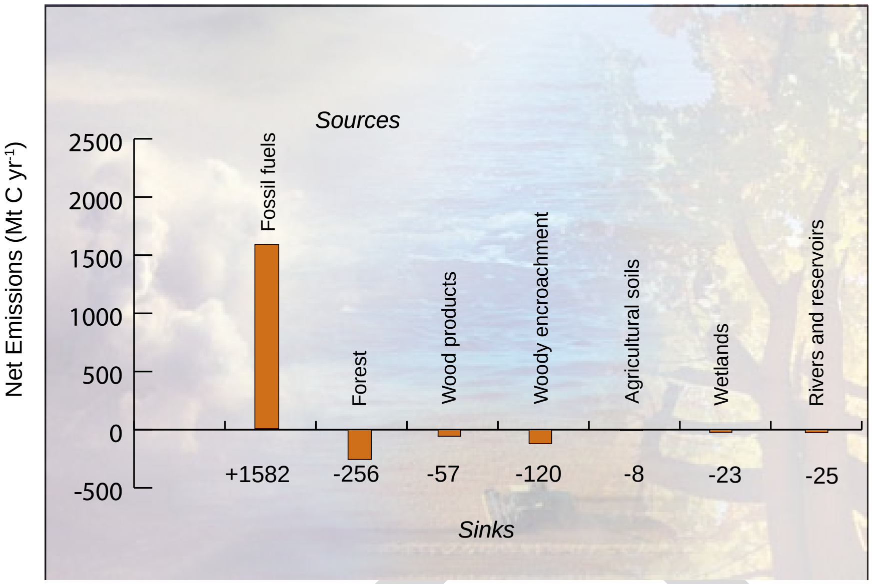


Courtesy of Kevin Gurney and the Vulcan Project (credit: C.C. Miller), Purdue University
Support provided by NASA (Carbon/04-0325-0167) and USDOE (DE-AC02-05CH11231)

Carbon dioxide is the most important of the greenhouse gases produced directly by human activities. The map shows where U.S. carbon dioxide emissions came from in 2002.

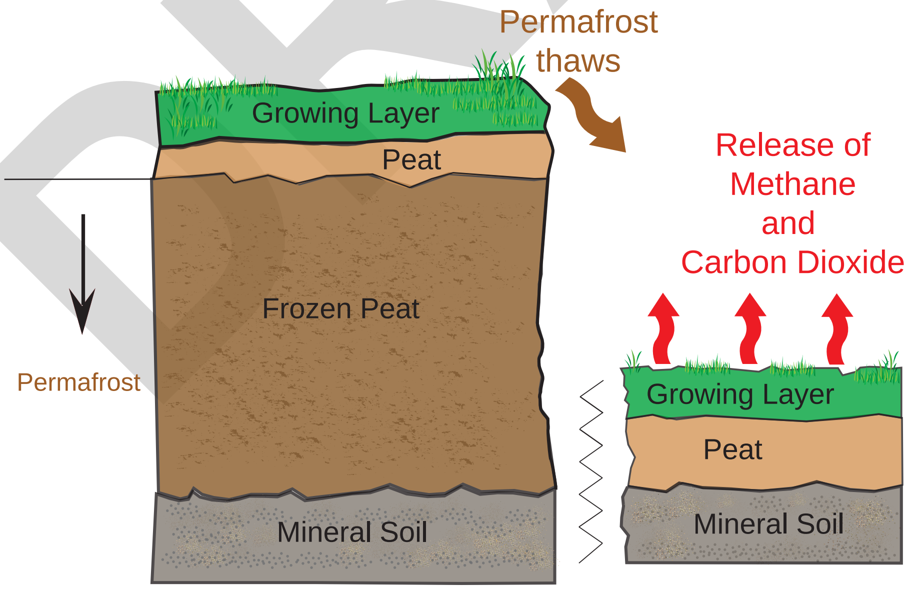
There are significant uncertainties in these estimates, and the amount of carbon taken up or released from natural sources varies considerably from year to year depending on climatic and other conditions. For example, fires release carbon dioxide so years with many large fires result in more carbon release and less uptake. Similarly, the trees destroyed by intense storms or droughts release carbon dioxide, and are also not available to absorb it in the future. For example, Hurricane Katrina killed or severely damaged over 320 million large trees. As these trees decompose over the next few years, they will release an amount of carbon equivalent to the carbon taken up by all U.S. forests in a year[7]. The net change in carbon storage in the long run will depend on the regrowth as well as the original disturbance.

U.S. Carbon Sources and Sinks



U.S. carbon sources and sinks in millions of tons of carbon per year in 2003. Sources add carbon dioxide to the atmosphere while sinks remove it.

Methane from livestock accounts for about 20% of total U.S. methane emissions. A potentially far larger source of methane is the thawing of permafrost (frozen soil) in Alaska. In arctic bogs where plants grow during the summer, old plant material sinks and forms peat. In permafrost areas, old peat is frozen and preserved. Over thousands of years, this process has gradually built up and stored a great deal of carbon in a layer of peat averaging a couple of yards thick. The thawing of permafrost due to warming will cause this peat to decompose, releasing methane and carbon dioxide. The potential is enormous: Alaska's permafrost contains ten times more carbon than is released each year by U.S. fossil fuel burning, and Canada has 10 times more carbon currently locked in permafrost than does Alaska.



Society

- Population movements and development choices are among the societal changes that are making more Americans vulnerable to climate change impacts.
- Vulnerabilities to climate change impacts are greater for those who have few resources and few choices.
- Climate change will affect the tourism and recreation industries in ways that reduce opportunities for many activities that Americans hold dear.
- Cities, both their residents and their infrastructure, have unique vulnerabilities to climate change.
- The insurance industry is particularly vulnerable to increasing extreme weather events, but can also help society manage the risks.

Key Sources

CCSP 3.3 Extremes
CCSP 3.4 Abrupt Climate Change
CCSP 4.1 Sea Level Rise
CCSP 4.6 Health
CCSP 4.7 Transportation
IPCC WG-2
GAO 2007 Insurance
GAO Alaska Villages
NAST U.S. Impacts

Climate change will affect society through impacts on the necessities and comforts of life: water, food, energy, health, transportation, recreation, insurance, and so on. Many of these topics are dealt with in some detail later in this report. This section focuses on various aspects of society that tend to integrate the impacts of climate change in ways that significantly affect quality of life.

Because societies and their built environments have developed in concert with a relatively stable historical climate, most impacts of a rapidly changing climate will present challenges and the adaptation required will involve costs. Society is especially vulnerable to extremes, such as heat waves and floods, many of which are increasing as climate changes. And while there are likely to be some benefits and opportunities in the early stages of warming, as climate continues to change, negative impacts are projected to dominate.

It is also important to recognize that the impacts of climate change do not affect society in isolation, but rather in combination with the impacts of other human-induced stresses such as pollution and poverty. Climate change will affect different segments of society differently due to their varying exposures and capacities to adapt. Wealthier segments are likely to have greater technical and financial resources, making them capable of considerable adaptation, but this requires effective planning and investment.

Unequal adaptive capacity in the world as whole will also pose challenges to the United States, as poorer countries are disproportionately affected and the U.S. has to cope with the world beyond its borders.

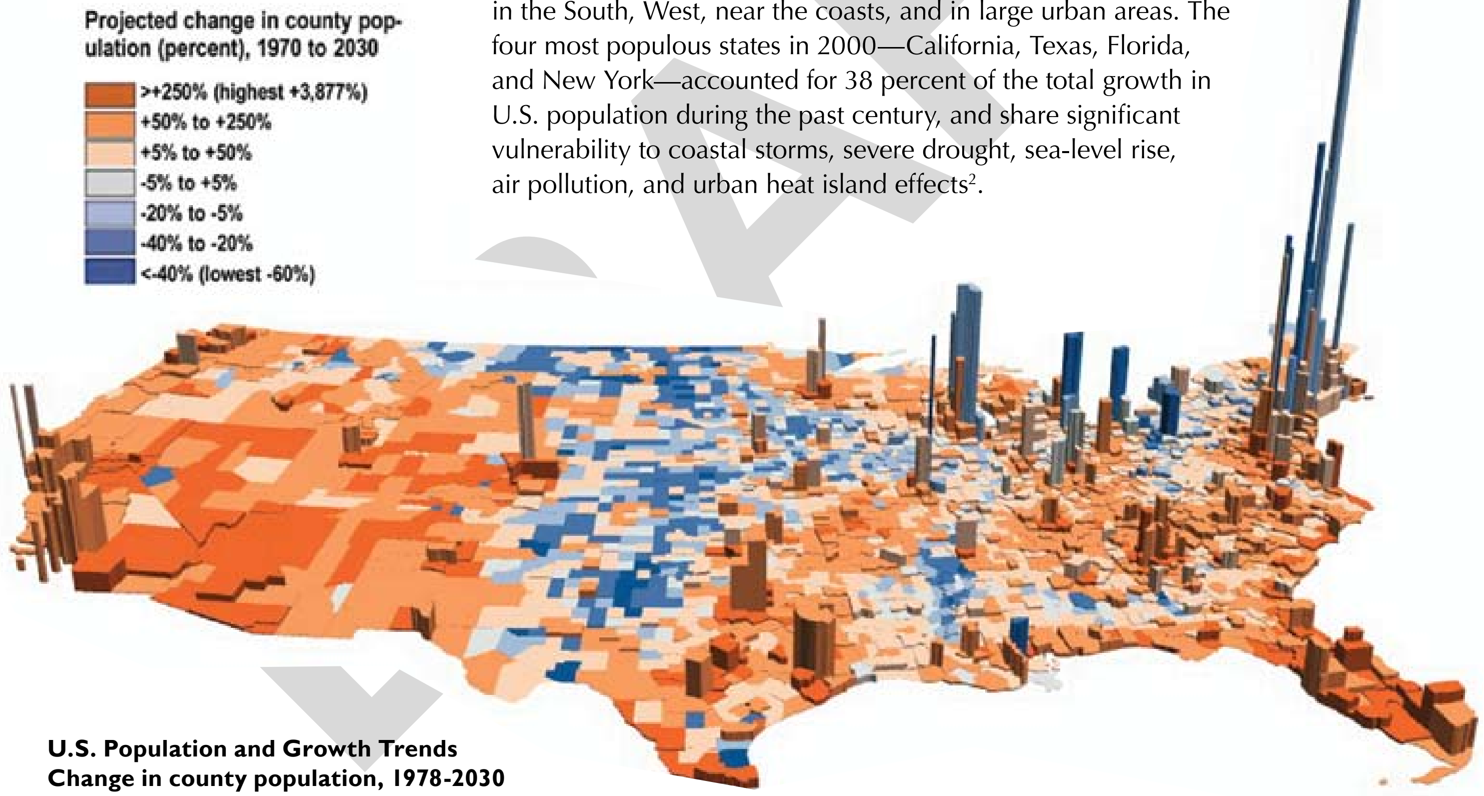
Population movements and development choices are among the societal changes that are making more Americans vulnerable to climate change impacts.

Climate change is interacting with changes in the U.S. population to affect all aspects of the human condition. As the challenges presented by population growth, an aging population, migration patterns, and urban and coastal development meet increasing changes in temperature, precipitation, sea levels, and extreme weather events, we can expect mounting impacts on many of the things we care about.

Overlaying projections of future climate change and its impacts on expected changes in U.S. population and development patterns reveals a critical insight: more Americans will be living in the areas that are most vulnerable to the effects of climate change. For example, the most rapidly growing area of the country is the mountainous West, a region projected to face more frequent and severe wildfires and have less available water, particularly during the high-demand period of summer. Similarly, the most rapidly growing coastal areas tend to be in regions most at risk due to hurricane activity, sea-level rise, and storm surge, putting more people and property in harm's way, even as the probability of harm increases[1].

Climate change is interacting with changes in the U.S. population to affect all aspects of the human condition.

U.S. population growth over the past century has been most rapid in the South, West, near the coasts, and in large urban areas. The four most populous states in 2000—California, Texas, Florida, and New York—accounted for 38 percent of the total growth in U.S. population during the past century, and share significant vulnerability to coastal storms, severe drought, sea-level rise, air pollution, and urban heat island effects[2].



U.S. Population and Growth Trends
Change in county population, 1978-2030

Each block on the map illustrates one county in the United States The height of each block is proportional to that county's population density in the year 2000, so the volume of the block is proportional to the county's total population. The color of each block shows the county's projected change in population between 1970 and 2030, with shades of orange denoting increases and blue denoting decreases. The patterns of recent population change, with growth concentrated along the coasts, in cities, and in the South and West, are projected to continue[38].

Population movement to arid regions will stress water supplies, especially in the mountainous West, desert Southwest, and Great Plains. Overuse of rivers and streams in the West is common in dry regions with high agricultural irrigation demands, especially those along the eastern front of the Rocky Mountains in Colorado, in Southern California, and in the Central Valley of California. In the 40 years from 1960 to 2000, Colorado's population grew by 245 percent. Rapid population and economic growth in these dry regions has dramatically increased vulnerability to water shortages (see *Water* sector and *Southwest* region)[3]. The population of the mountain West (Montana, Idaho, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico) is projected to increase by 65 percent from 2000 to 2030.

Regional Spotlight: Atlantic and Gulf Coast Vulnerability

America's coastlines have seen pronounced population growth in recent decades: 53 percent of the U.S. population now lives in the 17 percent of the land in coastal areas. On the Atlantic and Gulf coasts where hurricane activity is prevalent, the land is sinking while sea level is rising, and human activities are exacerbating the loss of coastal wetlands that once helped buffer the coastline from erosion due to storms. The devastation caused by recent hurricanes highlights the vulnerability of these areas.

Many questions are raised by ongoing development patterns in the face of climate change. Will growth continue as projected in vulnerable areas, despite the risks? Will there be a retreat from the coastline as it becomes more difficult to insure vulnerable properties? Will there be the usual pressure for the government to insure properties that private insurers have rejected? How can the vulnerability of new development be minimized? How can we ensure that communities adopt measures to manage the significant changes that are projected in sea level, temperature, rainfall, and extreme weather events?

Development choices are based on what society wants to create: places to live, economies that provide employment, and resources that support environmental protection and community-based social activities. Development paths emerging from these choices affect the severity of climate change impacts, not only through changes in climate-related exposure and sensitivity, but also through changes in capacities to adapt. This also means that the future vulnerability of society will be influenced by choices of development paths. But not all development choices are created equal. Some, such as expanded urban development in coastal regions, can increase vulnerabilities to climate-related events, even without any change in climate. At the same time, it is important to consider whether climate change would make it more difficult for regions and communities to achieve their long-term development goals, and whether some development paths are better than others in reducing climate-related vulnerabilities and increasing capacities to adapt. While the atmosphere is changing above our heads, the ground is also shifting beneath our feet.

Vulnerabilities to climate change impacts are greater for those who have few resources and few choices.

Vulnerabilities to climate change depend not only on where people are but also on who they are. For example, the experience with Hurricane Katrina showed that effects of severe weather events are much greater on those in the population who have limited ability to get out of harm's way, such as the elderly and poor. Thus, those who have the least, often lose the most. And it is clear that people with access to financial resources, including insurance, have a greater capacity to adapt to and recover from adverse climate change effects than the poor. The fate of the poor can be permanent dislocation, leading to the loss of social relationships provided by their schools, churches, and neighborhoods.

In general, especially vulnerable groups include the very young, the very old, the sick, the poor, and the powerless. These groups represent a more significant portion of the total population in some regions and localities than others. Communities of the very poor or elderly are thus likely to be particularly vulnerable to climate change effects. Often such communities are in marginal locations, such as in river flood plains or low-lying coastal areas, increasing their risk.

There are also some activities that are particularly sensitive to changes in climate, and those whose livelihoods depend on such activities are especially vulnerable to the impacts of climate change. For example, maple syrup production is heavily reliant on climate and recent warming has altered the required temperature patterns, shifting production northward from New England into Canada (see *Northeast* region). Similarly, cranberries require a long winter chill period, which is shrinking as climate warms[4].

Spotlight on Alaska Coastal Villages at Risk

Dozens of villages on the Alaska coastline are threatened by a combination of impacts caused by warming. Sea level is rising, the reduction in sea ice leaves the coast more vulnerable to wave action from storms, and the thawing of coastal permafrost makes the coast more easily eroded. The people of these villages tend to live traditional lifestyles, meaning that they hunt, fish and gather much of their food. Warming is reducing the availability and accessibility of many of these food sources, such as seals that live on ice, and caribou whose migration patterns are sensitive to changes in climate.

A number of villages are now facing the prospect of having to abandon their ancestral homes and relocate to safer ground. The costs of such relocations are estimated in the hundreds of millions of dollars per village, and it is not clear who would pay these costs. A U.S. government study found that 184 villages on the coast and in low-lying areas along rivers are subject to increased flooding and erosion due to warming. These vulnerable populations face losing their communities, their livelihoods, and in some cases, their culture, which depends on traditional ways of collecting and sharing food[5].

Climate change will affect the tourism and recreation industries in ways that reduce opportunities for many activities that Americans hold dear.

Recreation and tourism play important roles in the economy and quality of life of many Americans. In regions including the West, Alaska, and the Islands, tourism and recreation are major job creators, bringing billions of dollars to regional economies. Across the nation, fishing, hunting, skiing, snowmobiling, diving, beach-going, and other outdoor activities make important economic contributions and are a part of family traditions that have value that goes beyond the financial.

A changing climate will mean reduced opportunities for many of the activities that Americans hold dear[6]. For example, coldwater fish species such as salmon and trout that are popular with fishermen will have reduced habitat in a warmer world, and coral reefs are already severely compromised. Hunting opportunities will change as animals' habitats shift and as relationships among species in natural communities are disrupted by their different responses to rapid climate change. In the arid Southwest, which is projected to get drier, declining reservoir levels will affect boaters, and streams that support sport fisheries are likely to decline.

Outdoor activities make important economic contributions and are a part of family traditions that have value that goes beyond the financial.

Examples of economic impacts include a projection that a 20 percent reduction in skiing days in the Northeast would cost the region about $800 million a year in lost revenue, and jeopardize the financial viability of some resorts[7]. A recent analysis projects that along the southern North Carolina coast, 14 of the 17 recreational beaches will be permanently underwater by 2080 as sea-level rise erodes the coastline all the way to the road.

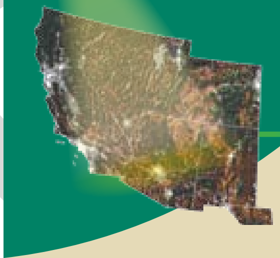
Lost opportunities for beach trips and fishing trips are projected to result in reduced recreational benefits totaling $3.9 billion in that state over the next 75 years[8].

There are opportunities for increases in some warm weather recreational options, but some of these options will be limited due to the increase in very hot weather.

Spotlight on Snowmobiling in the Northeast

Snowmobiling is the most vulnerable of the Northeast's economically important winter recreation activities, because, unlike the ski industry, it cannot be assisted by machine-made snow. Within the next several decades, snowmobiling opportunities are projected to become virtually nonexistent in Pennsylvania and much of New York state. By late in this century, the average season length for snowmobiling is projected to decline to just 13 days under a high-emissions scenario, an 80 percent decline below recent levels, and to 25 days under a low emissions scenario, a 57 percent decline. Only northern New Hampshire would retain a snowmobiling season longer than two months under a high emissions scenario.

Spotlight on Skiing in the West



The Mountain West is projected to see a continuation of the observed trend toward warmer winters and shorter snow seasons. Winter sports dependent on snow, including downhill skiing and snowboarding, cross-country skiing, snowshoeing, and snowmobiling are expected to see worsening conditions, potentially becoming unviable as soon as 2050 in some locations. Any significant shortening of the snow season is likely put some ski areas out of business. For example, a ski resort like Aspen is open for about 140 days; it takes the resort 100 days to break even and cover costs. If the season is compressed by a few dozen days, the resort can become unprofitable[9].

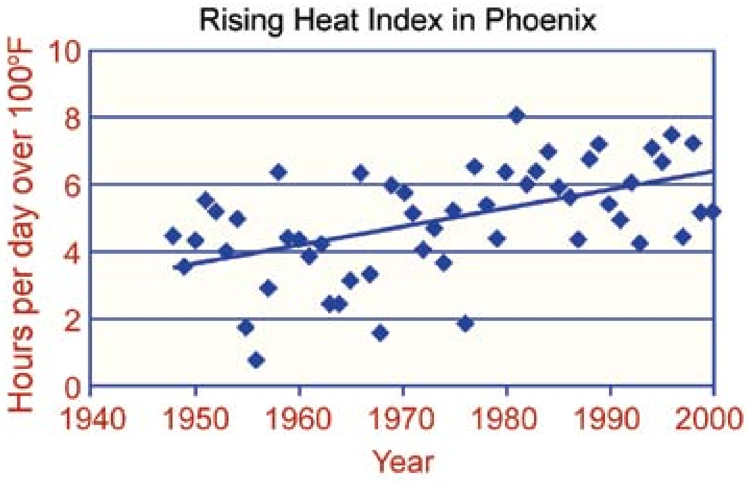
Cities, both their residents and their infrastructure, have unique vulnerabilities to climate change.

Over 80 percent of the U.S. population resides in urban areas. During recent decades, cities have become increasingly spread out, complex, and interconnected with regional and national economies[10]. Cities also have a host of social problems, including neighborhood degradation, traffic congestion, crime, poverty, and inequities in health and well-being[11]. Urban vulnerabilities to climate change are related to cities' economic activities, transportation, utility infrastructure, and residential populations. Climate-related changes including increased heat, air pollution, and extreme weather events will add further stress to existing problems.

Urban areas are among the most rapidly changing environments on Earth. As cities grow, they affect local climates. The urban heat island effect has raised average urban air temperatures by 2 to 5°F more than surrounding areas over the past 100 years, and by up to 20°F more at night[12]. Such temperature increases, on top of the general increase caused by human-induced warming, affect urban dwellers in many ways, influencing their health, comfort, energy costs, air quality, water quality and availability, and violent crime (which increases at high temperatures)[13,14].

The impacts of climate change on urban centers interact with and are compounded by cities' aging infrastructure, buildings, and populations, air pollution, and population growth. Their locations makes some cities more vulnerable than others. Cities are bellwethers of climate impacts, microcosms of the kinds of changes we can expect to see more widely in the future. For example, most cities already experience higher nighttime temperatures than surrounding areas due to the urban heat island effect. And some cities, particularly those in the western United States, are already facing the effects of drought on water availability.

The projected rise in extreme high temperatures combined with the urban heat island effect will increase stresses on urban residents. U.S. cities can expect to see longer, more frequent, and more intense heat waves, which will increase heat-related illness and death, and aggravate cardiovascular, respiratory, and other conditions (see *Human Health* sector). In Chicago's 1995 heat wave that resulted in over 700 deaths, most of the dead were elderly, inner-city poor, a group at increased risk of death due to heat stress. Climate projections suggest that the likelihood of a 1995-type heat wave will increase substantially over this century, with Chicago experiencing such heat waves three times per year under a high emissions scenario and every other year in a low emissions scenario (see *Midwest* region)[17].



The average number of hours per summer day in Phoenix that the Heat Index was over 100°F has doubled over the past 50 years. Hot days take a toll: Arizona's heat-related deaths are 13 times the national average[15].

More frequent heavy downpours and floods in urban areas will cause greater property damage, a heavier burden on emergency management, increased clean-up and rebuilding costs, and a growing financial toll on businesses and home owners. The Midwest floods of 2008 provide a recent vivid example of such tolls. Heavy downpours and floods can also overwhelm sewer and storm water systems. Typically, these systems have been engineered based on past frequency and intensity of rainfall, which are now increasing.

Coastal cities are at risk due to sea-level rise, storm surges, and increased hurricane intensity. Since most large U.S. cities are on coasts, rivers, or both, climate change will lead to increased flood potential. Cities such as New Orleans, Miami, and New York are particularly at risk, and would have difficulty coping with the sea-level rise projected under a high emissions scenario. The largest impacts are expected when sea-level rise, heavy river flows, high tides, and storms coincide[5]. Unfortunately, for many cities, current planning is based on the historical one-in-100 year event, and does not account for this same flood level occurring every 3 to 4 years as a result of the climate change projected over this century[18].

An increase in summer air conditioning use is projected to lead to a significant overall increase in electricity demand (see *Energy* sector). There is the potential for increased summer electricity blackouts such as those that have occurred in New York City and St. Louis. In southern California's cities, additional summer electricity demand will intensify conflicts between hydropower and flood-control objectives[18]. Unreliable electric power, as in minority neighborhoods during New York City's 1999 heatwave, can amplify concerns about health and environmental justice.

Coastal cities are at risk due to sea-level rise, storm surges, and increased hurricane intensity.

Infrastructure designed to handle past variations in climate can instill a false confidence in its ability to handle future changes. Urban economies and infrastructure are likely to be affected by climate change in unforeseen ways, such as through rising expenses to city health systems to cope with increased summer hospital admissions due to excessive heat and poor air quality, and diversion of city funds from capital projects and social programs to cope with necessary emergency responses to extreme weather. Increased costs of repairs and maintenance are projected for transportation systems including roads, railways, and airports as they are negatively affected by heavy downpours and extreme heat (see *Transportation* sector). An increase in urban crime is associated with higher temperatures, thus requiring additional police presence.

Adaptation Strategies

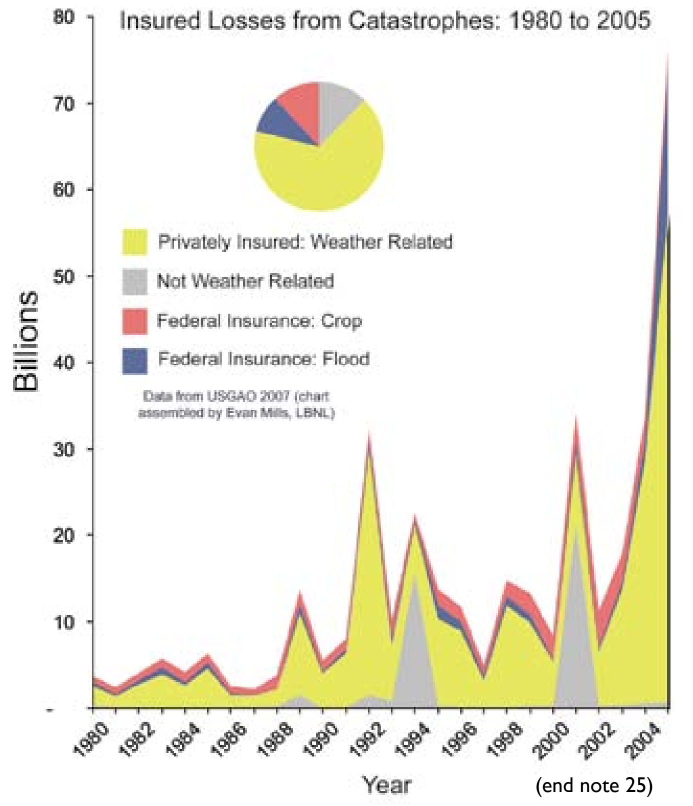
Cities concentrate the human activities that are largely responsible for heat-trapping emissions. The demands of urban residents are also associated with a much larger footprint on areas far removed from these population centers[19]. Cities thus have a large role to play in reducing heat-trapping emissions, and many are pursuing such actions. For example, over 700 cities have committed to the U.S. Mayors' Climate Protection Agreement to advance emissions reduction goals.

Urban areas also have considerable potential to adapt to climate change through technological, institutional, and behavioral changes. For example, a number of cities have programs in place to reduce heat-related illness and death (see *Human Health* sector). Choosing road materials that can handle higher temperatures is an adaptation option (see *Transportation* sector). The urban heat island effect compounds the effect of temperature increases due to global warming. Cities can reduce the heat load through reflective surfaces and green spaces. Some actions have multiple benefits. For example, increased planting of trees and other vegetation in cities has been shown to be associated with a reduction in crime[20], in addition to reducing local temperatures.

The insurance industry is particularly vulnerable to increasing extreme weather events, but can also help society manage the risks.

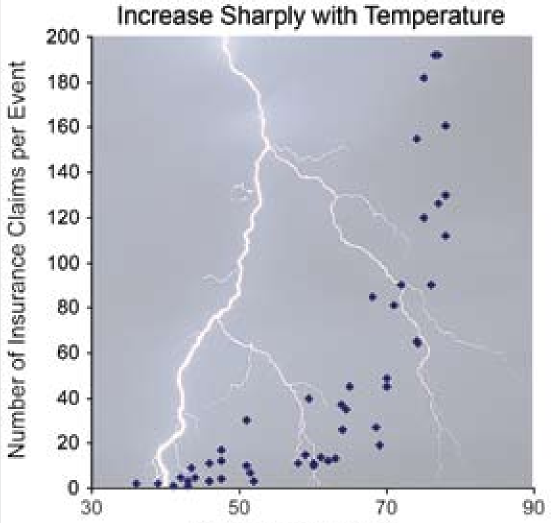
Most of the climate-change impacts described in this report have economic dimensions. A significant portion of these are channeled through the insurance sector, which serves as a risk-aggregating and risk-spreading vehicle for society and a window onto the myriad ways in which the costs of climate change will manifest. Government insurance programs for crops and flood absorb an additional layer of the overall risk.

Insurance provides peace of mind and financial security for many Americans. The highly weather-sensitive insurance industry (the world's largest at $4 trillion in yearly revenues as of 2006, about a quarter of which is from the United States) has been described as a lightning rod for the impacts of extreme weather events, serving as an integrator of impacts across all sectors of the economy and a messenger of these impacts through the terms and price signals it sends its customers[21]. Insurers provide comprehensive data on the costs of extreme weather events[22]. In an average year, about 90 percent of insured catastrophe losses worldwide are weather-related and the magnitude of these losses is growing. About half of all economic losses in the United States are insured; these are shown on the accompanying chart. Data on smaller-scale losses (many of which are weather-related) are significant but not included here[23].



(end note 25)

Insurers also embody the increasing globalization of climate risks. Because large American companies operate around the world, they are exposed to climate impacts wherever they occur. In turn, most of the growth in the insurance industry is in emerging markets, which will increase U.S. insurers' exposure to risk.



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It is a challenge to design insurance systems that properly price risks, reward loss-prevention, and do not inadvertently foster risk-taking (for example by repeatedly rebuilding flooded homes). Properly addressing these issues can correct market failures that have contributed to society's vulnerability to climate change. Yet, rising losses[24] are affecting the availability and affordability of insurance. Several million customers in the United States who can no longer find coverage in the private market have had to take refuge in state-mandated insurance pools, or go without insurance altogether.

While unwelcome, these insurer responses should come as no surprise to the extent that insurers are experiencing rising financial risks and communicating those to the rest of society through dramatic increases in prices, higher deductibles, and more exclusions. Private and federal insurers paid more than $320 billion in claims on weather-related losses in the United States from 1980 through 2005[25].

While major events like hurricanes grab headlines, the aggregate effect of smaller events including power outages, lightning strikes, and wildfires, account for 60 percent of total insured losses on average[21]. In the case of lightning, there is a strong correlation between higher temperatures and the severity of losses.[25??]

Weather-related losses are increasing much faster than population, inflation, and insurance penetration[27]. Damages from U.S. storms grew 60-fold to $6 billion a year between the 1950s and the 1990s[28] and there has been a seven percent annual increase in flood losses (corrected for inflation) since 1970[29]. These observations reinforce a recurring theme in this report: we can no longer use the past as the basis for planning for the future.

Virtually all segments of the insurance industry are vulnerable to the impacts of climate change: damage to onshore and offshore property and transportation infrastructure, crops and livestock, business and supply-chain interruptions, equipment breakdown, data loss, environmental liability, life, and health insurance. Risks to insurers and their customers include reduced periods of time between loss events, changing types and location of events, damages that increase exponentially with weather intensity, abrupt nonlinear changes, widespread simultaneous losses, and more events with multiple consequences. For example, the European heat wave of 2003 caused simultaneous impacts including enormous human death tolls and illness, wildfires, massive crop losses, and the curtailment of electric power plants and associated business interruptions due to high water temperatures or the lack of cooling water[31].

Insurers are also exposed to liability losses through legal claims from parties seeking compensation for the costs of climate change-related damages[32]. The assets that insurers' need to tap when paying losses (approximately $18 trillion worldwide) are also vulnerable to catastrophic losses.

Federal insurance exposures have grown substantially. For example, since 1980, the National Flood Insurance Program's exposure has quadrupled, nearing $1 trillion. Such escalating exposures to catastrophic weather events, coupled with private insurers' withdrawal from various markets are leaving the federal government at increased financial risk. For example, if the widespread Midwest floods of 1993 were to occur today, losses would be five times greater[33]. Following more than 250,000 flood claims in 2005 related to Hurricanes Katrina, Rita and Wilma, the National Flood Insurance Program would have gone bankrupt without being given the ability to borrow about $20 billion from the United States Treasury[34].

Insurers are emerging as partners in the scientific enterprise and the formulation of public policy and adaptation strategies[35]. Some have promoted adaptation by providing premium incentives for customers who fortify their properties, engaged in the process of determining building codes and land-use plans, and participated in the development and financing of new technologies and practices. Some insurers have also recognized that mitigation (emissions reduction) and adaptation can work hand in hand in a coordinated climate risk-management strategy[36,37].

Human Health

- Significant increases in illness and death related to extreme heat and heat waves are projected, along with small decreases in cold-related impacts.
- Health impacts due to reduced air quality are projected to be an increasing problem, especially in urban areas.

- Physical and mental health impacts due to extreme weather events are projected to increase.
- Infectious diseases borne by food, water, and insects are projected to increase.

- Allergies and asthma are on the rise, with climate change expected to play an increasing role in the future.
- Certain groups, including children, the elderly, and the poor, are most vulnerable to the range of health effects.

Key Sources CCSP 3.2 Climate Projections | CCSP 3.3 Extremes | CCSP 4.3 Impacts | CCSP 4.5 Energy | CCSP 4.6 Health | IPCC WG-1 | IPCC WG-2 | ACIA Arctic Impacts

Global warming poses unique challenges to human health. Unlike health threats caused by a particular toxin or disease pathogen, climate change affects multiple pathways that lead to harmful exposures. There are direct health impacts from heat waves and severe storms, ailments caused less directly as warming exacerbates air pollution and airborne allergens, and many climate-sensitive infectious diseases.

Increased risks associated with diseases originating outside the United States must also be considered because we live in an increasingly globalized world. Many poor nations are expected to suffer even greater health consequences from climate change. With global trade and transport, however, disease flare-ups in any part of the world can potentially reach the United States. In addition, weather and climate extremes such as severe storms and drought, can undermine public health infrastructure, further stress environmental resources, destabilize economies, and potentially create security risks both internally and internationally.

Significant increases in illness and death related to extreme heat and heat waves are projected, along with small decreases in cold-related impacts.

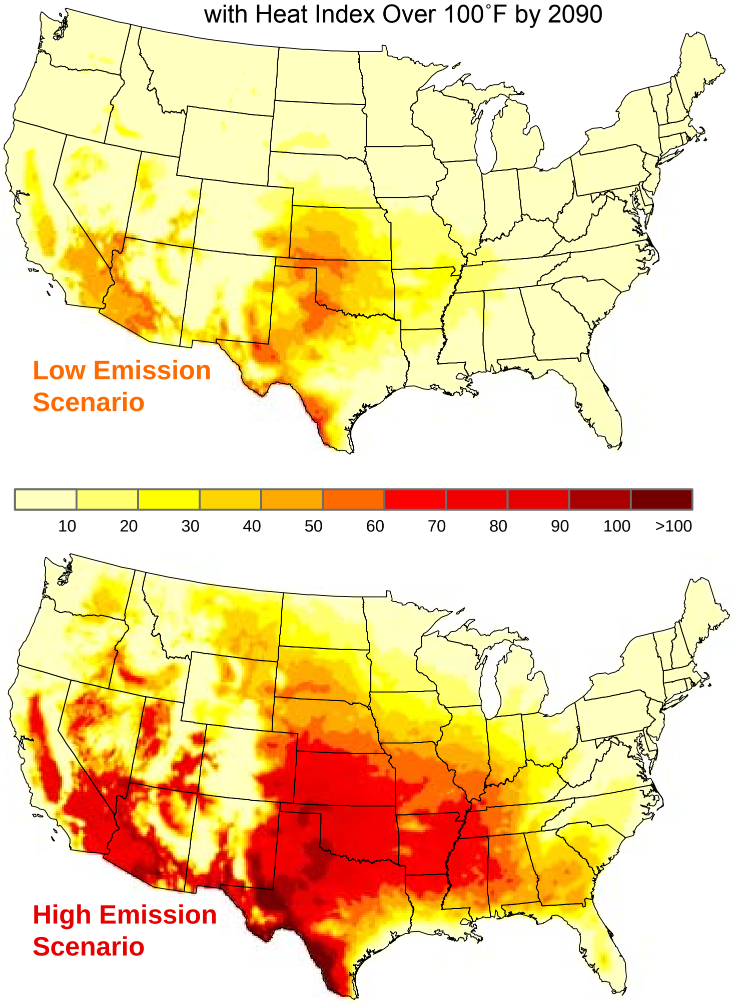
Temperatures are rising and the probability of severe heat waves is increasing. Analyses suggest that currently rare extreme heat waves will become much more commonplace in the future. At the same time, the U.S. population is aging, and older people are more vulnerable to hot weather and heat waves. The percentage of the U.S. population over age 65 is projected to be 13 percent by 2010 and 20 percent by 2030 (over 50 million people)[1], growing dramatically as the Baby Boomers join the ranks of the elderly[2]. Diabetics are also at greater risk of heat-related death and the prevalence of obesity and diabetes is increasing.

Heat is already the leading cause of weather-related deaths in the United States, responsible for more than 3,400 deaths between 1999 and 2003. As human-induced warming is projected to raise average temperatures by about 6 to 11°F in this century, heat waves are expected to increase in frequency, severity and duration in portions of the U.S. where they already occur. For example, the number of heat wave days in Los Angeles is projected to double if emissions are not reduced.

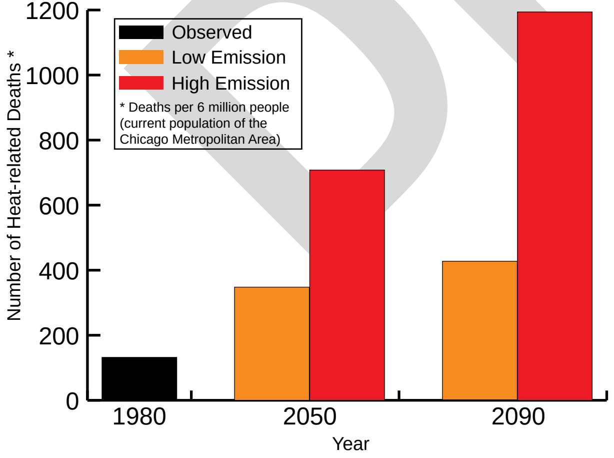
A recent analysis of 21 U.S. cities found that the average number of deaths due to heat waves would more than double by 2050, even though it accounted for changes made to adjust to the increased heat such as limiting outdoor activities, increasing fluid intake, and purchasing and using air conditioners. The greatest increases in deaths are projected to occur in mid-latitude major cities including New York, Chicago, and Philadelphia. Over 10,000 additional heat wave deaths due to global warming are projected for just those three cities by 2050, with over 23,000 additional deaths projected for the 21 cities studied[3]. Higher emissions scenarios result in higher death tolls while lower emissions would result in far fewer deaths.

The full effect of global warming on heat-related illness and death involves a number of factors: actual changes in temperature (averages, high and lows); human population characteristics such as age, wealth, and fitness; and policies that affect urban design, transportation, and energy and water use. For example, projected increases in residential and industrial development will increase the urban heat-island effect in the absence of improved urban design and technologies to reduce heat loads.

Projected Increase in the Number of Days with Heat Index Over 100˚F by 2090



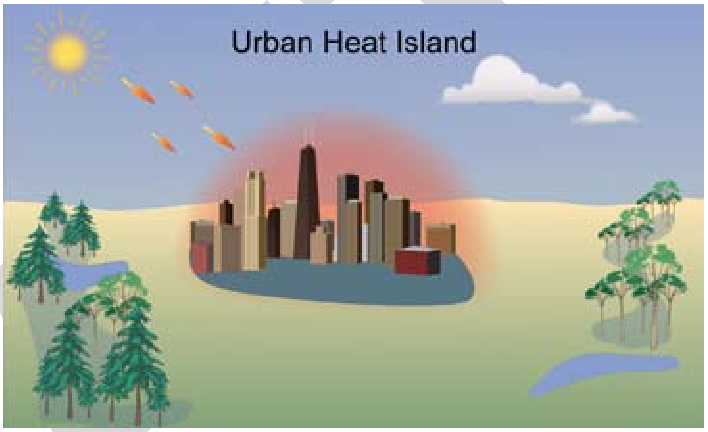
Projected Increases in Heat-Related Deaths in Chicago



Adaptation Strategies

Some U.S. cities have implemented systems for reducing the risk of death during heat waves, notably Philadelphia, the first to adopt such a system in the mid 1990s. The city focuses its efforts on the elderly, homeless, and poor. During a heat wave, the health department issues a heat alert and contacts news organizations with tips on how vulnerable people can protect themselves. The health department and thousands of block captains use a buddy system to check on elderly residents in their homes, electric utilities are barred from shutting off services for non-payment, and public cooling places extend their hours. The city operates a "Heatline" where nurses are standing by to assist callers experiencing health problems; if callers are deemed at-risk, mobile units are dispatched to the residence. The city has also implemented a "Cool Homes Program" for elderly low-income residents, which provides measures such as roof coatings and roof insulation that save energy and lower indoor temperatures. Philadelphia's system is estimated to have saved 117 lives over its first three years of operation[4].

The elderly are especially vulnerable to extreme heat.



Large amounts of concrete and asphalt in cities absorb and hold heat. Tall buildings prevent heat from dissipating and reduce air flow. At the same time, there is generally little vegetation to provide shade and evaporative cooling. As a result, parts of cities can be up to 10°F warmer than the surrounding suburban areas, compounding the temperature increases resulting from human-induced warming.

Reduced extreme cold

In a warmer world, extreme cold would be reduced and that could reduce the number of deaths caused by low temperatures. Research suggests that this effect would be relatively minor, however, probably because virtually all Americans have heat in their homes (as opposed to air conditioning, which is not universal). Current information on U.S. deaths due to extreme cold as well as extreme heat comes from recent research that analyzed daily mortality and weather data for 6,513,330 deaths in 50 U.S. cities between 1989 and 2000. The researchers found that, on average, cold snaps increased death rates by 1.6 percent, while heat waves triggered a 5.7 percent increase in death rates. Relatively milder winters attributable to global warming will not make up for the more severe health effects of summertime extremes[5].

It has been speculated that because death rates are higher in winter than in summer, warming might decrease deaths overall, but this ignores the fact that the principal causes of winter deaths are influenza and pneumonia, and it is unclear how these highly seasonal diseases are affected by temperature[6].

Health impacts due to reduced air quality are projected to be an increasing problem, especially in urban areas.

Poor air quality, especially in cities, is a serious concern across the United States. Half of all Americans live in counties where air pollution exceeds national health standards. Higher temperatures and related changes in climate increase pollutants such as ozone and very small particles (less than 2.5 micrometers in diameter) that cause heart and lung-related illnesses and deaths. It has been firmly established that breathing ozone results in short-term decreases in lung function and damages the cells lining the lungs. It also increases the incidence of asthma-related hospital visits and premature deaths. Vulnerability to ozone effects is greater for those who spend time outdoors, especially with physical exertion, because this results in a higher cumulative dose to their lungs. As a result, children, outdoor workers, and athletes are at higher risk for these ailments[7].

Ground-level ozone concentrations are affected by many factors including weather conditions, emissions of gases from vehicles and industries that lead to ozone formation, especially nitrogen oxides and volatile organic compounds (VOCs), natural emissions of VOCs from plants, and pollution blown in from other places[8]. A warmer climate is projected to increase the natural emissions of VOCs, accelerate ozone formation, and increase the frequency and duration of stagnant air masses that allow pollution to accumulate, which will exacerbate health symptoms.

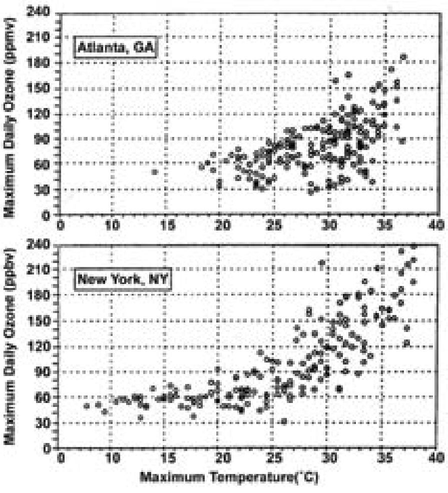
Increased temperatures and water vapor due to human-induced carbon dioxide emissions have been found to increase ozone more in areas with already elevated concentrations, meaning that global warming tends to exacerbate ozone pollution most in already polluted areas. The graphs illustrate the observed association between ground-level ozone concentration and temperature in Atlanta and New York City (May to October 1988-1990)[9].

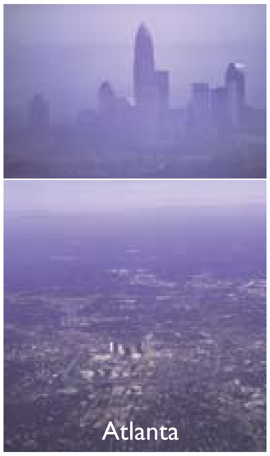
By the middle of this century, Red Ozone Alert Days (when the air is unhealthy for everyone) in the 50 largest cities in the Eastern U.S. are projected to increase by 68 percent due to warming alone[10]. The projected increases in stagnant air masses are projected to exacerbate this further[11].

The maps on the facing page show projected changes across the continental U.S., averaged over the summer months (June through August) under high and low emissions scenarios[13]. By themselves, higher temperatures and other projected climate changes would increase ozone levels under both scenarios. However, the maps indicate that future projections of ozone depend heavily on emissions[14], with the high emissions scenario increasing ozone by large amounts, while the low emissions scenario results in an overall decrease in ground-level ozone by the end of the century.

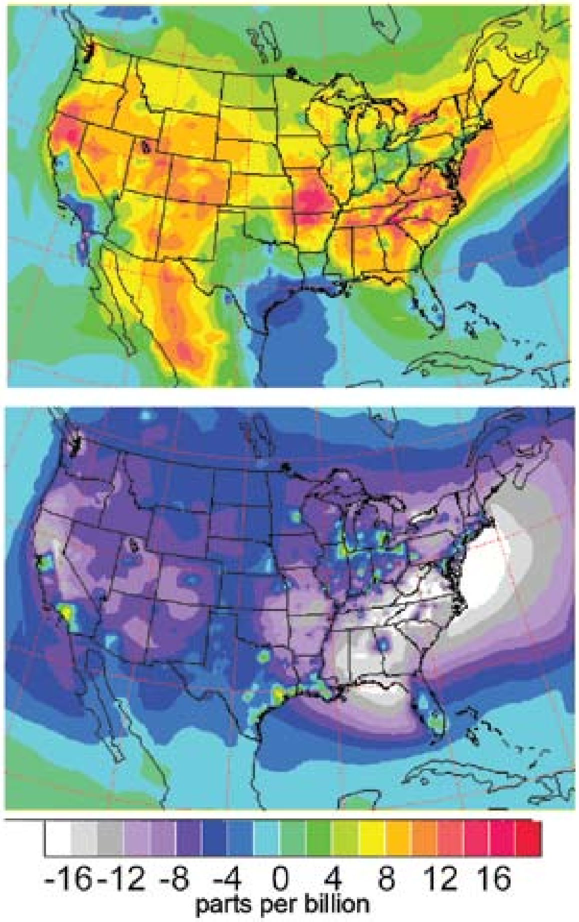
Very small particles (such as soot) arise from burning fossil fuels, principally coal and diesel fuel. These particles cause respiratory symptoms including coughing and difficulty breathing, decreased lung function, aggravated asthma, and development of chronic bronchitis, as well as heart ailments including heart attack and arrhythmia. The most susceptible people include children, older adults, and those with existing heart and lung disease and diabetes[15].

Maximum Daily Ozone Concentrations and
Maximum Daily Temperature in Atlanta and New York





Theses graphs illustrate the observed association between ground-level ozone concentrations and temperature in Atlanta and New York City (May to October 1988-1990). The projected higher temperatures across the U.S. in the 21st century are likely to increase the occurrence of high ozone concentrations, especially since extremely hot days frequently have stagnant air circulation patterns, although this will also depend on emissions of ozone precursors and meteorological factors. Ground-level ozone can exacerbate respiratory diseases and cause short-term reductions in lung function.



Projected changes in summer ground-level ozone for the 2090s relative to 1996-2000 under high emissions (top) and low emissions (bottom) scenarios[13].

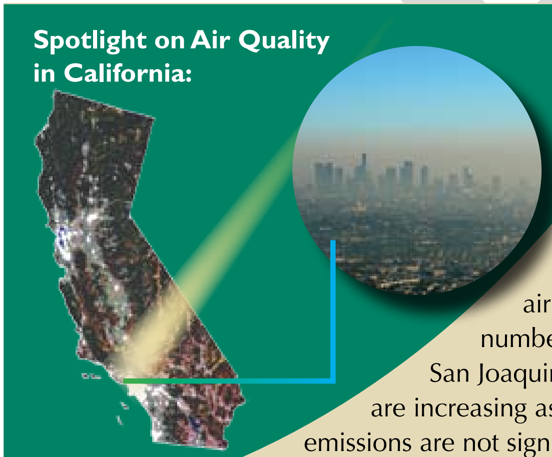
Adaptation Strategies

Like many other areas in the country, the Air Quality Alert program in Rhode Island encourages residents to reduce air pollutant emissions by limiting car travel and the use of small engines, lawn mowers, and charcoal lighter fluids. To help cut down on the use of cars, all regular bus routes are free on Air Quality Alert days. Television weather reports include alerts when ground-level ozone is high, warning especially susceptible people to limit their time outdoors.

Pennsylvania offers the following suggestions for high ozone days:

- Refuel vehicles after dark. Avoid spilling gasoline and stop fueling when the pump shuts off automatically.
- Conserve energy. Don't overcool homes. Turn off lights and appliances that are not in use. Wash clothes and dishes only in full loads.
- Limit daytime driving. Consider carpooling or taking public transportation. Properly maintain vehicles, which also helps to save fuel.
- Limit outdoor activities such as mowing the lawn or sports to the evening hours.
- Avoid burning leaves, trash and other materials.

Spotlight on Air Quality in California:



California currently experiences the worst air quality in the nation. More than 90 percent of the population lives in areas that violate air quality standards for ground-level ozone or small particles. These pollutants contribute to 8,800 deaths and $71 billion in health care costs every year in California. Higher temperatures are projected to increase the frequency, intensity and duration of conditions conducive to air pollution formation, potentially increasing by 75 to 85 percent the number of days conducive to air pollution formation in Los Angeles and the San Joaquin Valley. Air quality could be further compromised by wildfires, which are increasing as a result of warming. Recent analysis suggests that if heat-trapping emissions are not significantly curtailed, large wildfires could become up to 55 percent more frequent toward the end of this century[12].

Physical and mental health impacts due to extreme weather events are projected to increase.

Injury, illness, and death are projected to increase as the number and intensity of extreme weather events rises. Human health impacts in the United States are generally projected to be less severe than in poorer countries where the public health infrastructure is less developed. This assumes that medical and emergency relief systems in the U.S. will function well and that timely and effective adaptation measures will be developed and deployed. Of course, we have already seen serious failures of these systems in the aftermath of Hurricanes Katrina and Rita, so we must conclude that coping with future impacts will require significant improvements.

Extreme storms

Over 2,000 Americans were killed in the 2005 hurricane season, more than double the average number of lives lost to hurricanes in the U.S. over the previous 65 years. But the human health impacts of extreme storms go beyond direct injury and death to indirect effects such as carbon monoxide poisoning from portable electric generators in use following hurricanes, an increase in stomach and intestinal illness among evacuees, and mental health impacts such as depression and post-traumatic stress disorder. Failure to fully account for both direct and indirect health impacts may result in inadequate preparation for and response to future extreme weather events[16].

Floods

Heavy downpours have increased in recent decades and are projected to increase further as the world continues to warm. In the U.S., the amount of precipitation falling in the heaviest 1 percent of rain events increased by 20 percent in the past century, while total precipitation increased by 7 percent. Over the last century, there was a 50 percent increase in the frequency of days with precipitation over four inches in the upper Midwest[17]. Other regions, notably the South, have also seen strong increases in heavy downpours, with most of these coming in the warm season and almost all of the increase coming in the last few decades. Heavy rains can lead to flooding which can cause health impacts from direct injuries to increased incidence of water-borne diseases due to bacteria such as cryptosporidium and giardia.

Wildfires

Wildfires in the U.S. are already increasing due to warming. In the West, there has been a nearly fourfold increase in large wildfires in recent decades, with greater fire frequency, longer fire durations, and longer wildfire seasons[18]. This increase is strongly associated with increased spring and summer temperatures and earlier spring snowmelt, which have caused drying of soils and vegetation[19]. In addition to direct injuries and deaths due to burns, wildfires can cause eye and respiratory illnesses due to fire-related air pollution.

Infectious diseases borne by food, water, and insects are projected to increase.

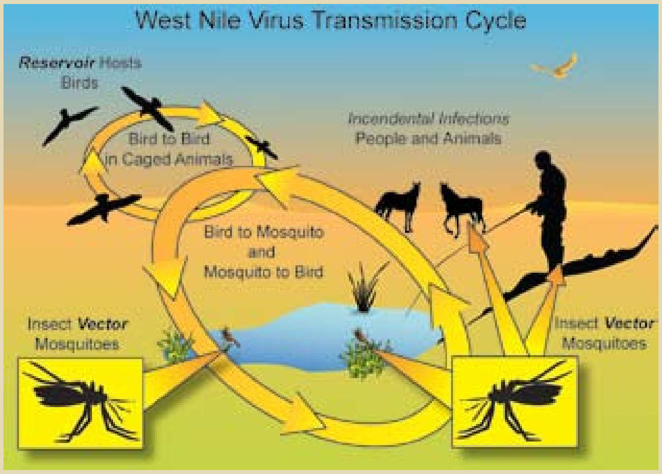
A variety of diseases carried by food, water, or animals like insects, birds, and rodents are projected to increase in a warmer world. A number of important disease-causing agents (pathogens) commonly transmitted by food, water, or animals, are susceptible to changes in replication, survival, persistence, habitat range, and transmission as a result of changing climatic conditions such as increasing temperature, precipitation, and extreme weather events.

- Cases of food poisoning due to *salmonella* and other bacteria increase with rising temperatures.
- Cases of water-borne *cryptosporidium* and *giardia* increase due to heavy downpours. These parasites can be transmitted in drinking water as well as through recreational water use[20].
- Climate change affects the abundance and distribution of the mosquitoes, ticks, and rodents that carry West Nile virus, Equine encephalitis, Lyme disease, and Hantavirus.
- Heavy rain and flooding can contaminate certain food crops with feces from nearby livestock or wild animals, increasing the incidence of food-borne disease associated with fresh produce.
- *Vibrio* accounts for 20 percent of the illnesses and 95 percent of the deaths associated with eating infected shellfish. There is a close association between temperature, *vibrio*, and clinical illness. The U.S. infection rate increased 41 percent from 1996 to 2006. Evidence suggests that rising temperatures will lead to an increased disease burden associated with *vibrio* in shellfish.

Spotlight on West Nile Virus

The first outbreak of West Nile virus in the U.S. occurred in the summer of 1999. The strain of West Nile virus that entered New York City that record hot July differed from other strains of the virus in that it required particularly high temperatures for efficient transmission. Within five years, the disease had spread across the continental United States, transmitted by mosquitoes that acquire the virus from infected birds. During the epidemic summers of 2002-2004 in the U.S., epicenters of West Nile virus were linked to above-average temperatures. Since 1999, West Nile had caused over 24,000 reported cases and over 1,000 Americans have died from it[21]

A more infectious and virulent strain of West Nile Virus has now evolved in the United States. The very hot summer of 2002 likely prompted the spread of this more dangerous, mutated strain. Recent analyses indicate that this strain responds strongly to higher temperatures, suggesting that greater risks from disease will result from future warming[21a].

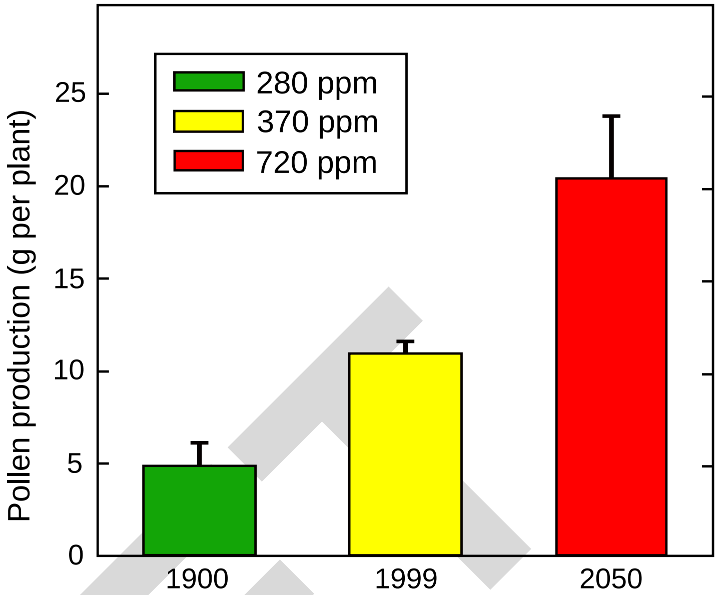


While West Nile virus causes mild flu-like symptoms in most people, about one in 150 infected people develop serious illness, including the brain inflammation diseases encephalitis and meningitis. Projected increases in heat waves portend increased risks from West Nile virus in the future. This disease also provides a good example of how globalization interacts with climate change to increase disease risks. West Nile Virus entered the U.S., probably as a result of international travel, and then responded to the hotter and drier conditions to present a new health threat.

Allergies and asthma are on the rise, with climate change expected to play an increasing role in the future.

There are over 700 plant species known to induce human illness[22]. Rising carbon dioxide levels have already been observed to increase the growth and toxicity of some that are very troublesome. For example, ragweed gets a disproportionately large boost from carbon dioxide compared to many beneficial plants. From a human health perspective, this mean a longer and more intense allergy season, and does not bode well for many asthma sufferers, because 70 percent of them also suffer from allergies and find their asthma exacerbated by allergies.

The observed increase in carbon dioxide levels has roughly doubled the amount of pollen that ragweed produces, and another doubling is projected to occur in this century if carbon dioxide levels continue to rise unrestrained. Pine trees are also projected to double their pollen production by the middle of this century.


Pollen Counts Rise with Increasing Carbon Dioxide

Pollen production from ragweed grown in chambers at carbon dioxide levels of a century ago (about 280 parts per million [ppm]). was about 5 grams per plant; at today's approximate carbon dioxide level, it was about 10 grams; and at a level projected to occur during this century if emissions are not reduced, it was about 20 grams[23].


Pollen on car

Poison ivy growth and toxicity is also greatly increased by carbon dioxide, with plants growing larger and more poisonous. These increases are much greater than those of most beneficial plants. For example, poison ivy vines grow twice as much per year in air with doubled pre-industrial carbon dioxide levels as in unaltered air, which is nearly five times the increase reported for tree species in other analyses[24]. Recent and projected increases carbon dioxide have also been shown to stimulate the growth of stinging net and leafy spurge, two weeds that cause rashes when they come into contact with human skin[25,26] .


Poison Ivy

Certain groups, including children, the elderly, and the poor, are most vulnerable to the range of health effects.

Infants and children, pregnant women, the elderly, people with chronic medical conditions, outdoor workers, and people living in poverty are especially at risk from increasing heat stress, air pollution, extreme weather events, and diseases carried by food, water and insects.

Children's small body mass to surface area ratio and other factors make them more vulnerable to heat-related illness and death. Their increased breathing rates relative to body size, time spent outdoors, and developing respiratory tracts heighten their sensitivity to air pollution impacts. In addition, children's immature immune systems increase their risk of serious consequences from water- and food-borne diseases, while developmental factors make them more vulnerable to complications from severe infections such as *E coli*.

Pregnant women have increased susceptibility to a variety of climate-sensitive infectious diseases including malaria and food-borne infections[27]. The greatest health burdens generally fall on the poor, who are more likely to have inadequate housing and to lack access to health care and air conditioning.

Some elderly people are frail and have limited mobility. The elderly are also generally more sensitive to extreme heat for several reasons. They have a reduced ability to regulate their own body temperature or sense when they are too hot. They are at greater risk of heart failure that is exacerbated when greater cardiac output is required for cooling during heat waves. They may also be on medications, such as diuretics for high blood pressure, increasing the risk of dehydration. People 65 years of age and older comprised 72 percent of the heat-related deaths due to the 1995 Chicago heat wave[28]. Older people are also more likely to have preexisting medical conditions that may put them at greater risk of harm from climate-related events or conditions.

The multiple health risks associated with diabetes will increase the vulnerability of the U.S. population to human-induced warming. The number of Americans with diabetes has grown to about 24 million people, or roughly 8 percent of the U.S. population. Almost 25 percent of the population 60 years and older had diabetes in 2007[29]. Fluid imbalance and dehydration create higher risks for diabetics during heat waves. People with diabetes related heart disease are at especially increased risk of dying in heat waves.

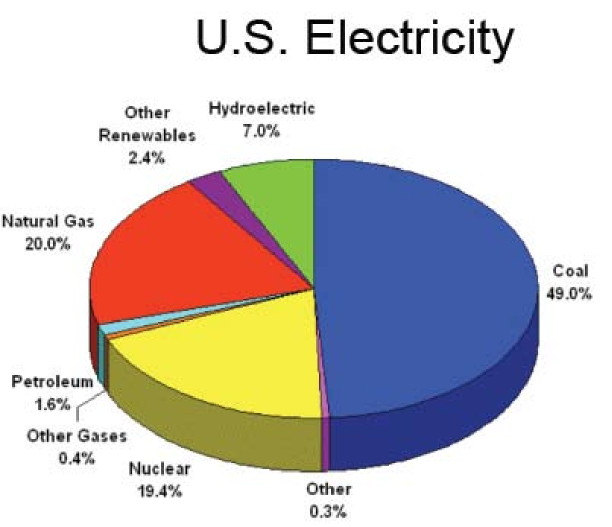
Adaptation Strategies

People who are more fit are better able to cope with heat stress. Thus, taking steps to reduce obesity is a strategy for adapting to a warmer world. High obesity rates in the United States are one cause of the current rise in diabetes. A factor in rising obesity rates is a sedentary lifestyle and automobile dependence; 60 percent of Americans do not meet minimum daily exercise requirements. Making cities more walk-able and bike-able would thus have multiple benefits: personal fitness and weight loss; reduced local air pollution and associated respiratory illness; and reduced greenhouse gas emissions.

Energy Production

- Warming will be accompanied by significant increases in electricity use and peak demand in most regions, due to increased demand for air conditioning.
- Energy production is dependent upon reliable water supply.
- Rising temperatures decrease power plant efficiency.
- Energy production and delivery systems are vulnerable to sea-level rise and extreme weather events in many regions.
- Climate change is likely to affect some renewable energy sources, especially hydropower.

placeholder for U.S. Energy consumption graph



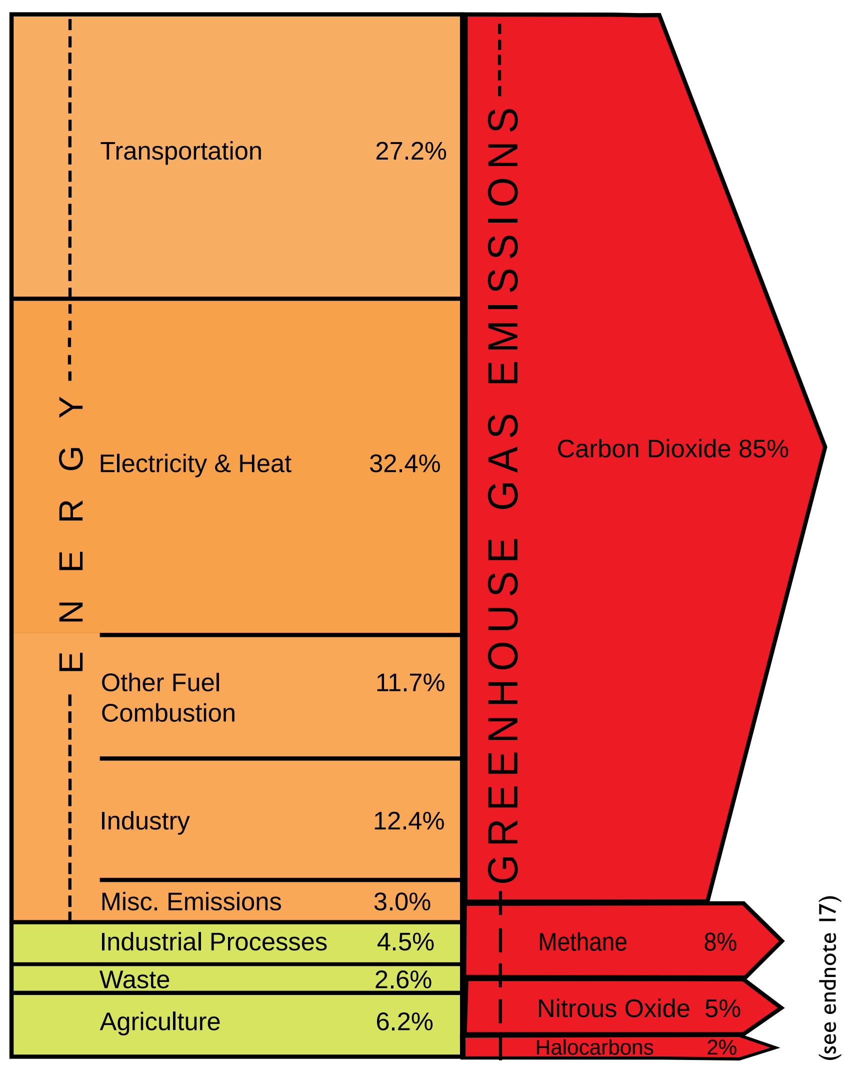
Key Sources CCSP 4.1 Sea Level Rise · CCSP 4.5 Energy · CCSP 4.7 Transportation · IPCC WG-1 · IPCC WG-2 · ACIA Arctic Impacts

and Use

Energy is at the heart of the global warming challenge. It is humanity's production and use of energy that is the primary cause of global warming, and in turn, warming will impact our production and use of energy. The vast majority of U.S. greenhouse gas emissions, about 87 percent, come from the energy sector[1-a].

At the same time, other U.S. trends are increasing energy use: population shifts to the South and West, an increase in the square footage built per person, increased electrification of the residential and commercial sectors, and increased market penetration of air conditioning.

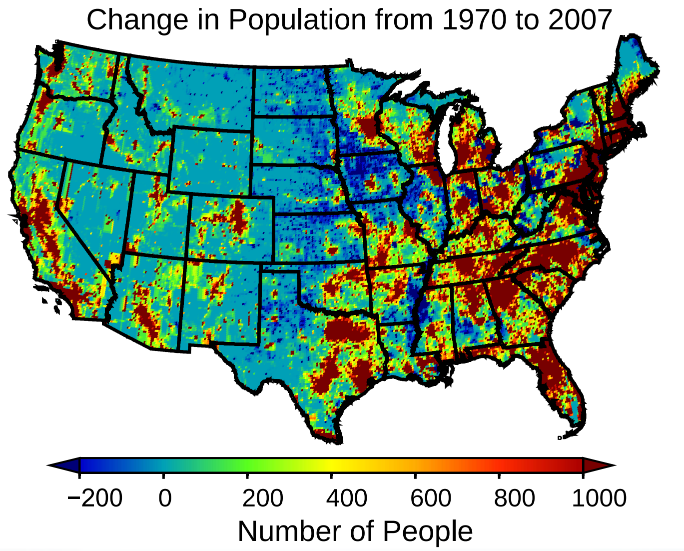
Global and national energy choices made in the coming years will largely determine the degree of future climate change. Policies to reduce greenhouse gas emissions will have implications for the energy sector, and these will in turn feed back to influence how the energy sector impacts climate.



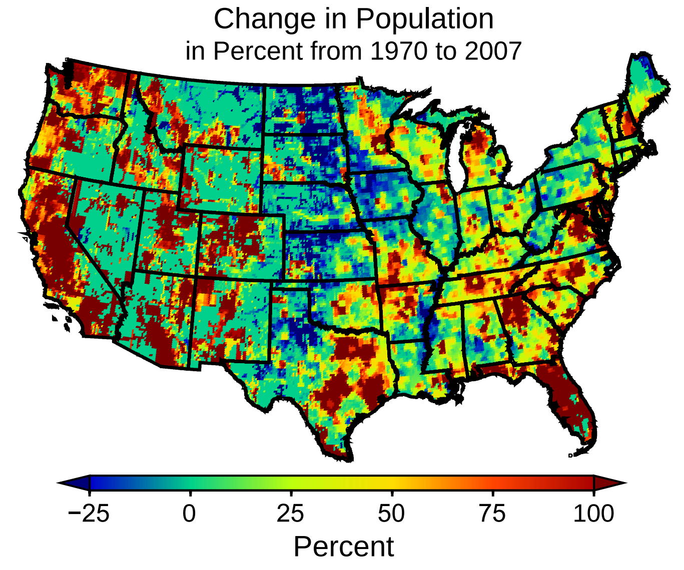
(see endnote I7)

First Draft - July 2008 Do not cite or quote

• Warming will be accompanied by significant increases in electricity use and peak demand in most regions, due to increased demand for air conditioning.



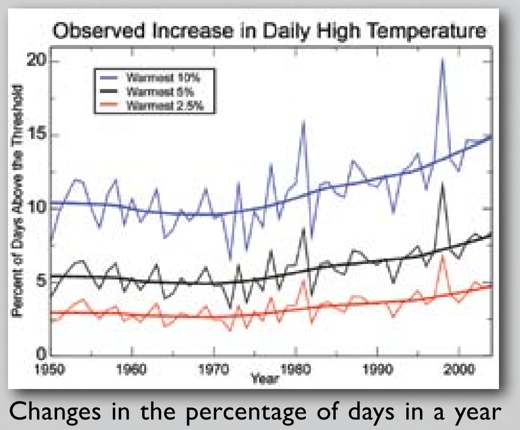
The map above, showing changes in numbers of people, graphically illustrates the large increases in population in places that require air conditioning. Areas with increases of more than 1000 people are all shown in maroon. Some of these places had enormous growth, in the hundreds of thousands of people. For example, parts of Los Angeles, Phoenix, Las Vegas, Dallas, Houston, and Miami all had increases of between 250,000 and 400,000 people.



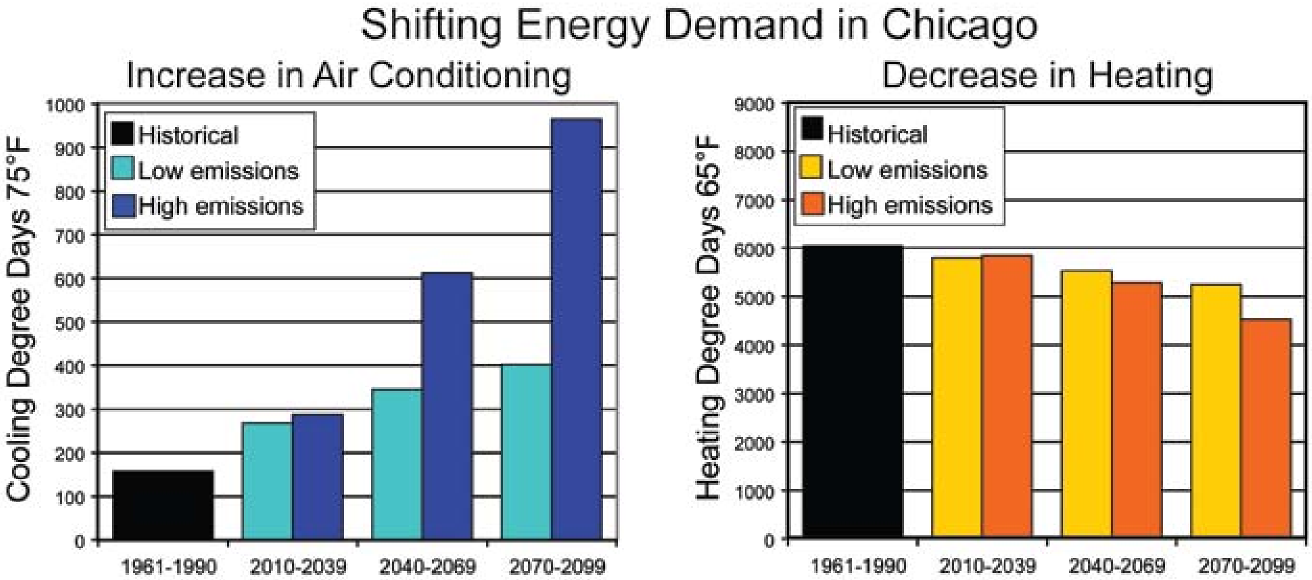
The map above, showing percentage changes in population, shows the very rapid growth in the South and Southwest. Places with increases over 100% growth are shown in maroon. Some areas, such as those around Orlando, Florida, and Denver, Colorado, had increases of 600%.

Energy use in U.S. buildings currently accounts for 38 percent of the nation's energy-related heat-trapping gas emissions. Studies that assess future changes in energy use as a result of global warming project an increase in electricity consumption and in the consumption of primary fuels used to generate it, except in the few regions that provide a considerable amount of space heating with electricity, such as the Pacific Northwest. Peak electricity demand is also projected to increase, causing a disproportionate increase in energy infrastructure investment.

In the southern part of the nation, electricity use for air conditioning is expected to increase more than heating fuel use decreases. In the northern part of the U.S., projected warming is expected to reduce consumption of heating fuel more than it increases the consumption of electricity. However, because air conditioning relies entirely on electricity, and the generation, transmission, and distribution of electricity is subject to significant energy losses, national primary energy demand is projected to increase with rising temperatures. And because 50 percent of the nation's electricity is generated with coal, which is the highest carbon fuel, carbon dioxide emissions are also projected to increase (unless concerted measures are taken to change the fuel mix or remove the carbon dioxide from coal-burning processes and store it under ground, as has been proposed). In addition, because population movements are generally toward the southern regions that require more air conditioning and away from those regions that require more heating, population shifts also contribute to an increasing trend in energy use.



Changes in the percentage of days in a year above three thresholds for North America for daily high temperature[15].



(see endnote 16)

A number of studies have considered effects of warming on energy requirements for heating and cooling in buildings in the United States. They find that the demand for cooling increases from 5 to 20 percent per 1.8°F of warming, and the demand for warming drops by 3 to 15 percent per 1.8°F of warming. The range reflects different assumptions about such factors as the rate of market penetration of improved building equipment technologies.

Since nearly all cooling is provided by electricity use, while much of our heating of buildings is provided by natural gas and fuel oil, the projected changes imply increased demands for electricity, especially in two kinds of areas: (1) where climate change would result in significant increases in the heat index, especially in summers, and (2) where relatively little space cooling has been needed in the past, but demands are likely to increase in the future.

Other effects of climate change on energy consumption are less clear, because little research has been done. For instance, warming would increase the use of air conditioners in highway vehicles, possibly reducing fuel efficiency, and water scarcity in some regions could increase energy demands for water pumping. Improving the information available about these other kinds of effects is a priority.

Energy production is dependent upon reliable water supply

In some regions, reductions in water supply could be significant, increasing the competition for water among various sectors including energy production (see *Water* sector). Operation of existing energy plants and development of future facilities could be restricted by water availability.

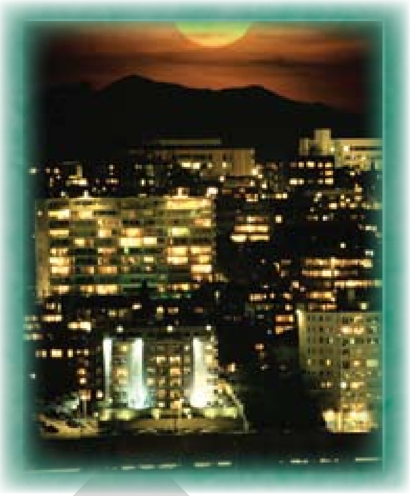
The production of energy from fossil fuels (coal, oil, and natural gas) is inextricably linked to the availability of adequate and sustainable supplies of water[3]. While providing the U.S. with the majority of its annual energy needs, fossil fuels also place a high demand on the nation's water resources in terms of both use and quality impacts[4]. Generation of electricity in power plants (coal, nuclear, gas, or oil) is water intensive; on average, each kilowatt-hour of electricity generated in a power plant requires about 25 gallons of cooling water. Power plants rank only slightly behind irrigation in terms of freshwater withdrawals in the United States[5].

Water is also required in the mining, processing, and transportation of coal to generate electricity, all of which can have direct impacts on water quality. Surface and underground coal mining can result in acidic, metal-laden water that must be treated before it can be discharged to nearby river and streams. In addition, in 2000, the mining industry withdrew about two billion gallons per day of fresh water.

There is a high likelihood of water shortages limiting power plant electricity production in many regions, projecting future water constraints on electricity production in power plants for Arizona, Utah, Texas, Louisiana, Georgia, Alabama, Florida, California, Oregon, and Washington state by 2025[5a]. Additional parts of the United States could face similar constraints as a result of drought, growing populations, and increasing demand for water for various uses. The issue of competition among various water uses is dealt with in more detail in the *Water* sector.

In addition to the problem of water availability, there are issues related to an increase in water temperature. Using warmer water as an input for power plants reduces the efficiency of cooling technologies, and warmer water as a receiver of water discharges could present environmental implications. And when power plants use water for cooling, they discharge that water at higher temperatures which has environmental implications. Large coal and nuclear plants have been limited in their operations by temperature-related river water level changes and thermal limits on water discharges[6].

Rising temperatures decrease power plant efficiency.



The efficiency of thermal power plants, fossil or nuclear, is sensitive to ambient air and water temperatures; higher temperatures reduce power outputs by affecting the efficiency of cooling. Although the effect is not large in percentage terms, even a relatively small change could have significant implications for total national electric power supply. For example, an average reduction of one percent in thermal power generation nationwide would mean 25 billion kWh/year, about the amount of electricity consumed by two million Americans, that would need to be supplied in some other way.

Regional Spotlight: Energy Impacts of Alaska's Rapid Warming

Significant impacts of warming on the energy sector can be found in Alaska, where temperatures have risen about twice as much as the rest of the nation. In Alaska, frozen ground and ice roads are an important means of winter travel and warming has resulted in a much shorter cold season. Serious impacts on the oil and natural gas industries on Alaska's North Slope have been one of the results. In addition, the thawing of permafrost, on which buildings, pipelines, airfields, and coastal installations supporting oil and gas development are located, adversely affects these structures and increases the cost of maintaining them.

Different energy impacts are expected in the marine environment as sea ice continues to retreat and thin. These trends are expected to improve shipping accessibility around the margins of the Arctic Basin, though not in a uniform fashion among the different regions. Extensive oil and gas reserves have been discovered in Alaska along the Beaufort Sea coast. Offshore oil exploration and extraction will probably benefit from less extensive and thinner sea ice, although equipment will have to be designed to withstand increased wave forces and ice movement[9].

Energy production and delivery systems are vulnerable to sea-level rise and extreme weather events in many regions.

Sea-level rise

A significant fraction of America's energy infrastructure is located near the coasts, from power plants, to oil refineries, to facilities that receive oil and gas deliveries. Rising sea levels are likely to lead to direct losses such as equipment damage from flooding or erosion and indirect effects such as the costs of raising vulnerable assets to higher levels or building new facilities further inland, thus increasing transportation costs[10]. The U.S. East Coast and Gulf Coast have been identified as particularly vulnerable to sea-level rise because the land is relatively flat and also subsiding in some places[11].

Extreme events

Observed and projected increases in a variety of extreme events will have significant impacts on energy. As witnessed in 2005, hurricanes can have a debilitating impact on energy infrastructure. Direct losses to the energy industry in 2005 are estimated at $15 billion[13], with millions more in restoration and recovery costs. As one example, the Yscloskey Gas Processing Plant was forced to close for six months following Hurricane Katrina, resulting in lost revenues to the plant's owners and employees, and higher prices to consumers as alternative gas sources had to be procured.

Regional Spotlight: Gulf Coast Oil and Gas

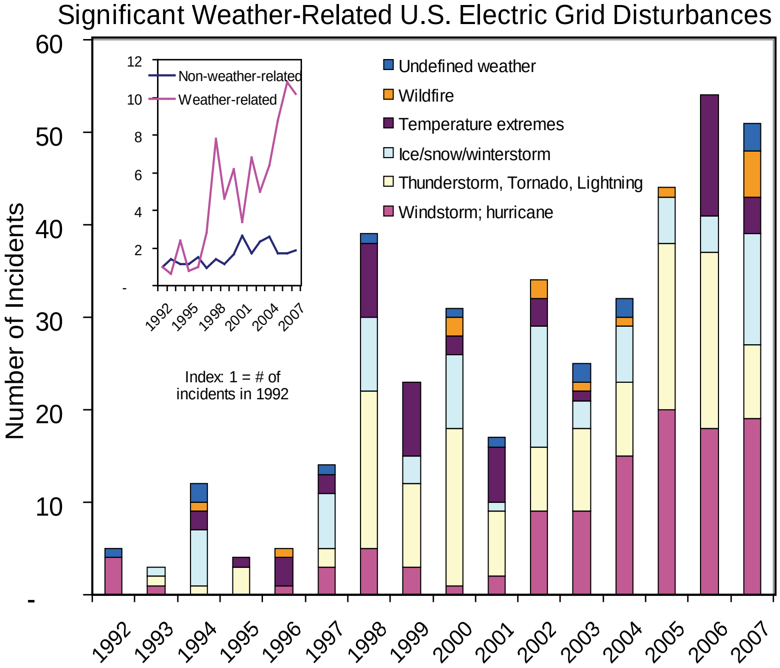
The Gulf Coast is home to the U.S. oil and gas industries, representing nearly 30 percent of the nation's crude oil production and approximately 20 percent of its natural gas production. A third of the national refining and processing capacity lies on coastal plains adjacent to the Gulf. Several thousand offshore drilling platforms, dozens of refineries, and thousands of miles of pipelines are vulnerable to damage and disruption due to sea-level rise and the high winds and storms surge associated with hurricanes and other tropical storms. For example, Hurricanes Katrina and Rita halted all oil and gas production from the Gulf, disrupted nearly 20 percent of the nation's refinery capacity, and closed many oil and gas pipelines[12].

Offshore production is particularly susceptible to extreme weather events. Hurricane Ivan in 2004 destroyed seven platforms in the Gulf of Mexico, significantly damaged 24 platforms, and damaged 102 pipelines. Hurricanes Katrina and Rita in 2005 destroyed more than 100 platforms and damaged 558 pipelines. The photos show Chevron's "Typhoon" platform before and after the 2005 hurricanes. The $250 million platform was damaged beyond repair. Plans are being made to sink its remains to the sea floor.

(see endnote 3)

The incapacitation of energy infrastructure due to the hurricanes of 2005, especially of refineries, gas processing plants, and petroleum product terminals, is widely blamed for driving a price spike in fuel prices across the country, with national consequences. The impacts of more severe weather are not limited to hurricane-prone areas. Rail transportation lines, which transport approximately two-thirds of the coal to the nation's power plants, often follow riverbeds, especially in the Appalachian region. More intense rainstorms, which have been observed and projected, can lead to flooding of rivers that can then wash out or degrade the nearby rail and roadbeds[14].

Flooding and drought can both disrupt the operation of inland waterways, the second-most important method for transporting coal. With utilities carrying smaller stockpiles and projections showing a growing reliance on coal for a majority of the nation's electricity generation, any significant disruption to the transportation network has serious implications for the over reliability of the electric grid (see *Transportation* sector).



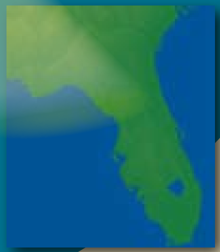
The number of incidents caused by extreme weather is up 10-fold since 1992. The portion of all events that are caused by weather-related phenomena has tripled from about 20 percent in the early 1990s to about 65 percent in recent years. The weather-related events are more severe, with an average of about 180,000 customers affected per event compared to about 100,000 for non-weather-related events (and 50,000 excluding the massive blackout of August 2003)[3].

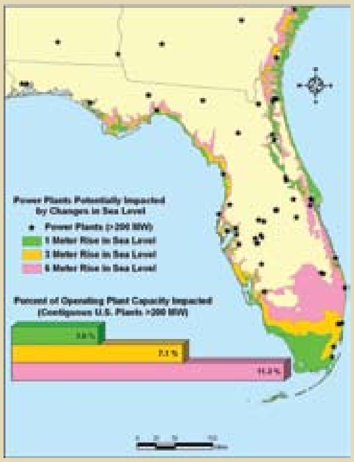
Development of new energy facilities could be restricted by siting concerns related to sea-level rise, exposure to extreme events, and increased capital costs resulting from a need to provide greater protection from extreme events.

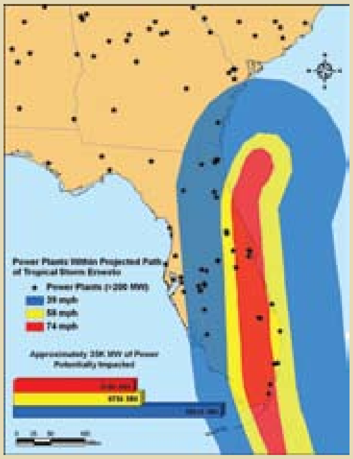
The electricity grid is also vulnerable to climate change effects, from temperature changes to severe weather events. The most familiar example is effects of severe weather events on power lines (e.g., from ice storms or tornadoes as well as hurricanes), but in the summer heat wave of 2006 electric power transformers failed in several areas, such as St. Louis and Queens, NY, due to high temperatures, causing interruptions of electric power supply. It is not yet possible to project effects of climate change on the grid, because so many of the effects would be more localized than current climate change models can depict; but weather-related grid disturbances are recognized as a challenge for strategic planning and risk management.

Regional Spotlight: Florida's Energy Infrastructure

Florida's energy infrastructure is particularly vulnerable to sea-level rise and storm impacts. Most of the petroleum products consumed in Florida are delivered by barge to three ports, two on the east coast of Florida and one on the west coast. The interdependencies of natural gas distribution, transportation fuel distribution and delivery, and electrical generation and distribution were found to be major issues in Florida's recovery from recent major hurricanes.







Climate change is likely to affect some renewable energy sources, especially hydropower.

Renewable energy production accounts for 9.4 percent of electricity production in the United States. Hydroelectric power is by far the largest renewable contributor to electricity generation, accounting for about 7 percent of total U.S. electricity. Like many things discussed in this report, renewable energy resources have strong interrelationships with climate change; using renewable energy can reduce the magnitude of climate change, while climate change can affect the prospects for using some renewable energy sources.

Hydropower is a major source of electricity in some regions of the U.S., particularly the Pacific Northwest. It is likely to be significantly affected by climate change. The year-to-year variation in hydropower generation is very high, especially relative to other energy sources. There is a 30 percent difference between recent high and low years for hydropower generation because the amount of water available for hydropower varies greatly from year to year. This amount depends upon weather patterns, local hydrology, and competing water uses such as flood control, water supply, recreation, and requirements for fulfilling downstream water rights, navigation, and the protection of fish and wildlife. Climate variability is the most important factor in the variability of hydropower.

Significant changes are already being detected in the flow regimes of many western rivers, consistent with the predicted effects of global warming. More precipitation coming as rain rather than snow, reduced snow pack, earlier peak runoff, and related effects are beginning to affect hydropower availability. Hydroelectric generation is very sensitive to changes in precipitation and river discharge. For example, every 1 percent decrease in precipitation results in a 1 percent drop in stream flow; every 1 percent decrease in stream flow in the Colorado River Basin results in a 3 percent drop in generation. Such magnifying sensitivities occur because water flows through multiple power plants in a river basin. Climate impacts on hydropower occur when either the total amount or the timing of runoff is altered, for example, when natural water storage in snow pack and glaciers is reduced under hotter conditions. Glaciers, snow pack, and their associated runoff are already declining in the U.S. West, and larger declines are projected.

Hydropower operations are also affected by changes to air temperatures, humidity, or wind patterns due to climate change. These variables cause changes in water quantity, quality, and temperature. Warmer air and water generally increases the evaporation of water from the surface of reservoirs, reducing the amount of water available for power production and other uses. Huge reservoirs with large surface areas, located in arid, sunny parts of the country, such as Lake Mead on the Colorado River, are particularly susceptible to increased evaporation due to warming, meaning less water will be available for all uses, including hydropower. And where hydropower dams flow into waterways that support trout, salmon or other cold-water fisheries, warming of reservoir releases may have unacceptable consequences that require changes in operations that reduce power production. Such impacts will increasingly present competition for resources.

Biomass energy now produces about 4 percent of total U.S. energy, mostly for industrial uses, though it may increase substantially in the future, given the current emphasis on ethanol and other biofuels for transportation.

If there were changes in wind resources and direct solar radiation, it would impact the planning, siting, and financing of wind and solar technologies. For example, some climate models project increases in cloudiness that have the potential to diminish the solar resource barring other counterbalancing effects; preliminary results based on one study suggest a 6 percent decrease in overall solar cell output. Atmospheric pollutant particles could further decrease the solar resource. Wind power could also be affected if there were warming-induced changes in the wind resource. Preliminary results from a limited number of studies suggest significant decreases may be expected in some places in some seasons though others suggest increases in some places and seasons. This is an area that requires much more study (see *Pathways to Improved Understanding*).

National Level Climate Impacts

Transportation

- Sea-level rise and storm surges are projected to result in major impacts including flooding of coastal airports, roads, rail lines, and tunnels.

- Increasingly intense downpours and related flooding will cause disruptions and delays in air, rail, and road transportation.

- The increase in extreme heat will limit some operations and cause pavement and track damage. Decreased extreme cold will confer benefits.

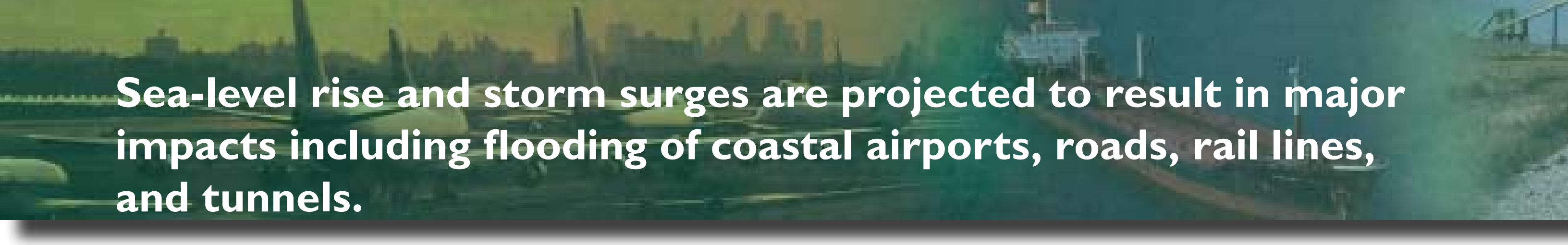
- Increased intensity of strong hurricanes would lead to more evacuations, damages, transportation interruptions, and a greater probability of infrastructure failure.

- Arctic warming reduces sea ice, lengthening the ocean transport season. Permafrost thaw in Alaska damages infrastructure. The ice road season becomes shorter.

Transport across the globe, and the U.S. transport sector in particular, is a significant source of greenhouse gases. Transportation accounts for 27.2% of U.S. greenhouse gas emissions[1], more than double the percentage it accounts for globally (13.1%)[2]. So while this discussion centers on the impacts of climate change on transportation, it should be noted that transportation also has a major impact on climate.

Climate change impacts on transportation also cause disruptions in other sectors across the economy. For example, major flooding, such as that in the Midwest in 2008 and 1993, restricts travel of all types, and these restrictions, in turn, impact freight and rail shipments across the country, from moving coal to power plants to bringing chlorine to water treatment systems.

Extreme events present major challenges for transportation and such events are becoming more frequent and intense. Historical weather patterns are no longer a reliable predictor of the future. Climate change must be considered in transportation planning and design.



Sea-level rise and storm surges are projected to result in major impacts including flooding of coastal airports, roads, rail lines, and tunnels.

U.S. transportation infrastructure in coastal areas is increasingly vulnerable to sea-level rise and storm surge. With 53 percent of the U.S. population living in the 17 percent of U.S. land that is in coastal counties[3] (a population density more than three times the national average[4]). The potential exposure of transportation infrastructure to flooding is immense. And population swells in the summer months as beaches are the top tourist destination[5].

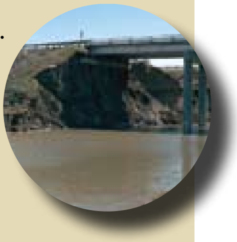
Coastal areas are projected to experience continued development pressures as both retirement and tourist destinations. Many of the most populous counties of the Gulf Coast, that already experience the effects of tropical storms, are expected to grow rapidly in the coming decades[6]. This growth will generate demand for more transportation infrastructure and increase the difficulty of evacuation in an emergency.

At the same time, sea-level rise will make transportation infrastructure in low-lying coastal areas even more vulnerable to extensive flooding and higher storm surges. An estimated 60,000 miles of coastal highway is already exposed to periodic flooding due to coastal storms and high waves[7]. Some of these highways currently serve as evacuation routes during hurricanes and other coastal storms, and these routes could become seriously compromised in the future.

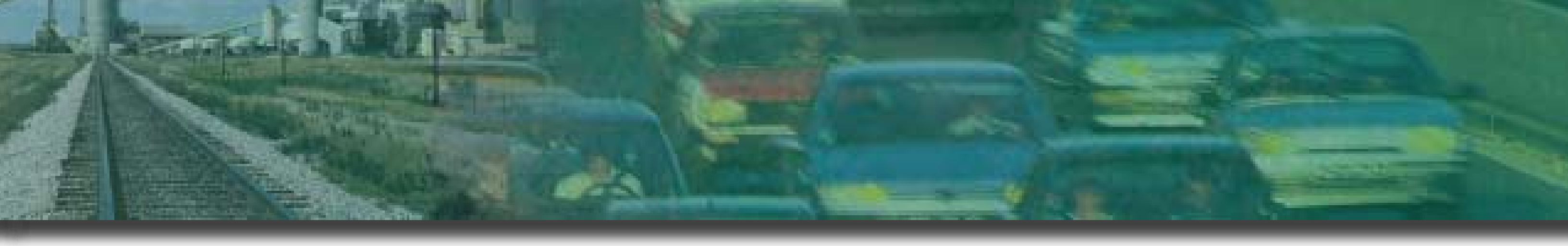
In the Gulf Coast area alone, an estimated 2,400 miles of major roadway and 246 miles of freight rail lines are projected to be underwater within 50 to 100 years, as global warming and land subsidence combine to produce relative sea-level rise in the range of four feet[8]. Since the Gulf transportation network is interdependent and relies on minor roads and other low-lying infrastructure, the service disruptions due to sea-level rise may be even greater than these significant levels indicate[9].

Regional Spotlight: the Gulf Coast

Sea-level rise will make much of the existing infrastructure more prone to frequent or permanent inundation; 27 percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports are built on land at or below four feet in elevation, a level within the range of projections for relative sea-level rise in this region in this century. Increased storm intensity may lead to increased service disruption and infrastructure damage: More than half of the area's major highways (64 percent of Interstates, 57 percent of arterials), almost half of the rail miles, 29 airports, and virtually all of the ports are below 23 feet in elevation and subject to flooding and possible damage due to hurricane storm surge. These factors should be considered in today's transportation decisions and planning processes[14].



Coastal areas are also major centers of economic activity. Six of the nation's top ten freight gateways (measured by the value of shipments) will be at risk from sea-level rise[10]. Seven of the ten largest ports (by tons of traffic) are located on the Gulf Coast[11]. The region is also home to the U.S. oil and gas industries, with its offshore drilling platforms, refineries, and pipelines. Roughly two-thirds of all U.S. oil imports are transported through this region[12] (see Energy sector).



Land

More frequent inundation and interruptions in travel on coastal and low-lying roadways and rail lines due to storm surges are projected. More frequent evacuations due to severe storm surges are also likely. Many cities have subways, tunnels, parking lots, and other transportation infrastructure below ground. Underground tunnels and other low-lying infrastructure will see more frequent and severe flooding. Higher sea levels and storm surges will also erode road base and undermine bridge supports. The loss of coastal wetlands and barrier islands will lead to further coastal erosion due to the loss of natural protection from wave action.

> *In some areas, waterway systems will become part of open water.*

Water

Impacts on harbor infrastructure from wave damage and storm surges are projected to increase. Changes will be required in harbor and port facilities to accommodate higher tides and storm surges. There will be reduced clearance under waterway bridges for boat traffic. Changes in the navigability of channels are expected; some will be more accessible (and farther inland) because of deeper waters, while others will be restricted because of changes in sedimentation rates and sandbar locations. In some areas, waterway systems will become part of open water. Some of them will likely have to be dredged more frequently as has been done across large open water bodies in Texas[13].

Air

Airports in coastal cities are often located adjacent to rivers, estuaries, or open ocean. Airport runways in coastal areas could be inundated. There is the potential for closure or restrictions for several of the nation's busiest airports that lie in coastal zones, affecting service to the highest density populations in the United States.

Regional Spotlight: New York Metro Area

With potential sea-level rise estimated under business-as-usual emissions to be up to 3.5 feet by 2080, the combined effect of sea-level rise and storm surge is projected to dramatically increase the frequency of flooding. What is currently called a 100-year storm is projected to occur as often as every four years. Portions of lower Manhattan and coastal areas of Brooklyn, Queens, Staten Island, and Nassau County would experience a marked increase in flooding frequency. Much of the critical transportation infrastructure, including tunnels, subways, and airports, lies well within the range of projected storm surges and would be under water during such events[15].

Increasingly intense downpours and related flooding will cause disruptions and delays in air, rail, and road transportation.

Heavy downpours have already increased substantially in the U.S.; the heaviest 1% of precipitation events increased by 20%, while total precipitation increased by 7%[21]. Such intense precipitation is likely to increase the frequency and severity of such events as the Great Flood of 1993 which caused catastrophic flooding along 500 miles of the Mississippi and Missouri River system, paralyzing surface transportation systems including rail, truck, and marine traffic. Major east-west traffic was halted for roughly six weeks in an area stretching from St. Louis west to Kansas City and north to Chicago, affecting one-quarter of all U.S. freight that either originated or terminated in the flood-affected region[22].

The June 2008 Midwest flood was the second "500-year event" in the past 15 years. Dozens of levees were breached or overtopped in Iowa, Illinois, and Missouri, flooding huge areas, including 1300 blocks of downtown Cedar Rapids, Iowa. Numerous highway and rail bridges were impassable due to flooding of approaches and transport was shut down along many stretches of highway and normally navigable waterways. Cost estimates are not yet available, but early indications suggests that this event will be one of the most expensive in U.S. history.

Land

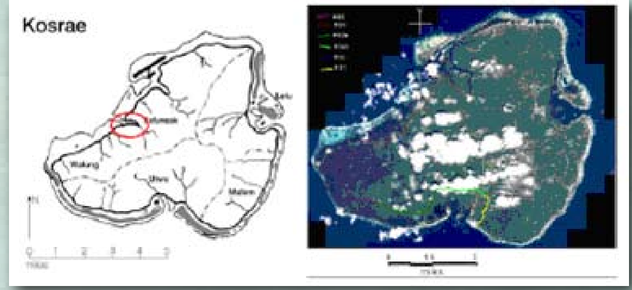
The increase in heavy precipitation will inevitably cause increases in weather-related accidents, delays, and traffic disruptions in a network already challenged by increasing congestion. There would be increased flooding of evacuation routes. Construction activities would be disrupted. There will be changes in rain, snowfall, and seasonal flooding that impact safety and maintenance operations on the nation's roads and railways. For example, if precipitation changes from snow to rain in winter and spring thaws, there will be increased risk of landslides, slope failures, and floods from the runoff, causing road closures.

Increased flooding of roadways, rail lines and underground tunnels is expected. Drainage systems will be overloaded more frequently and severely, causing backups and street flooding. Areas where flooding is already common will face much more frequent and severe problems. For example, Louisiana Highway 1, a critical link in the transport

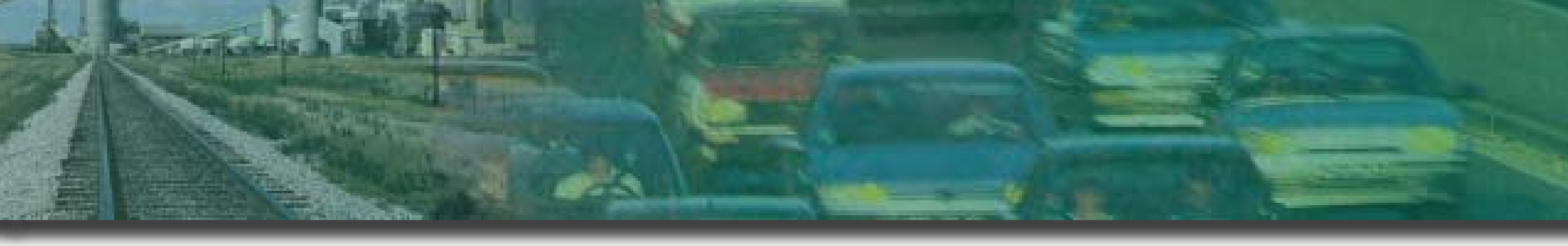
Adaptation: Climate-Proofing a Road

Completion of a road around the 42-square mile island of Kosrae in the U.S.-affiliated Federated States of Micronesia provides a good example of adaptation to climate change. A road around the island's perimeter existed, except for a ten-mile gap. Filling this gap would provide all-weather land access to a remote village and allow easier access to the island's interior.

In planning this new section of road, authorities decided to "climate proof" it against projected increases in heavy downpours and sea-level rise. This led to the section of road being placed higher above sea level and with an improved drainage system to handle the projected heavier rainfall. While there are additional capital costs for this drainage system, the accumulated costs, including repairs and maintenance, would be lower after about 15 years, equating to a good rate of return on investment. Adding this improved drainage system to roads that are already built is more expensive than on new construction, but still found to be cost-effective.



(see endnote 26)



of oil from the Gulf of Mexico, has recently experienced increased flooding, prompting authorities to elevate the structure[24]. Increases in road washouts, damage to rail bed support structures, and landslides and mudslides that damage roads and other infrastructure are expected. If soil moisture levels become too high, the structural integrity of roads, bridges, and tunnels could be compromised. Standing water will have adverse impacts on road base. For example, damage due to long term submersion of roadways in Louisiana was estimated to be $50 million for just 200 miles of state-owned highway. The Louisiana Department of Transportation and Development noted that a total of 1800 miles of roads were under water for long periods, requiring costly repairs[25]. Pipelines are likely to be damaged as intense precipitation can cause the ground to sink underneath the pipeline; in shallow riverbeds, pipelines are more exposed to the elements and can be subject to scouring and shifting due to heavy precipitation.

Water

Increased delays due to heavy downpours will affect operations. As these events increase, flight delays at major airports will increase as well. Changes in silt and debris buildup resulting from extreme precipitation events will affect channel depth, increasing dredging costs.

Regional Spotlight on the Midwest

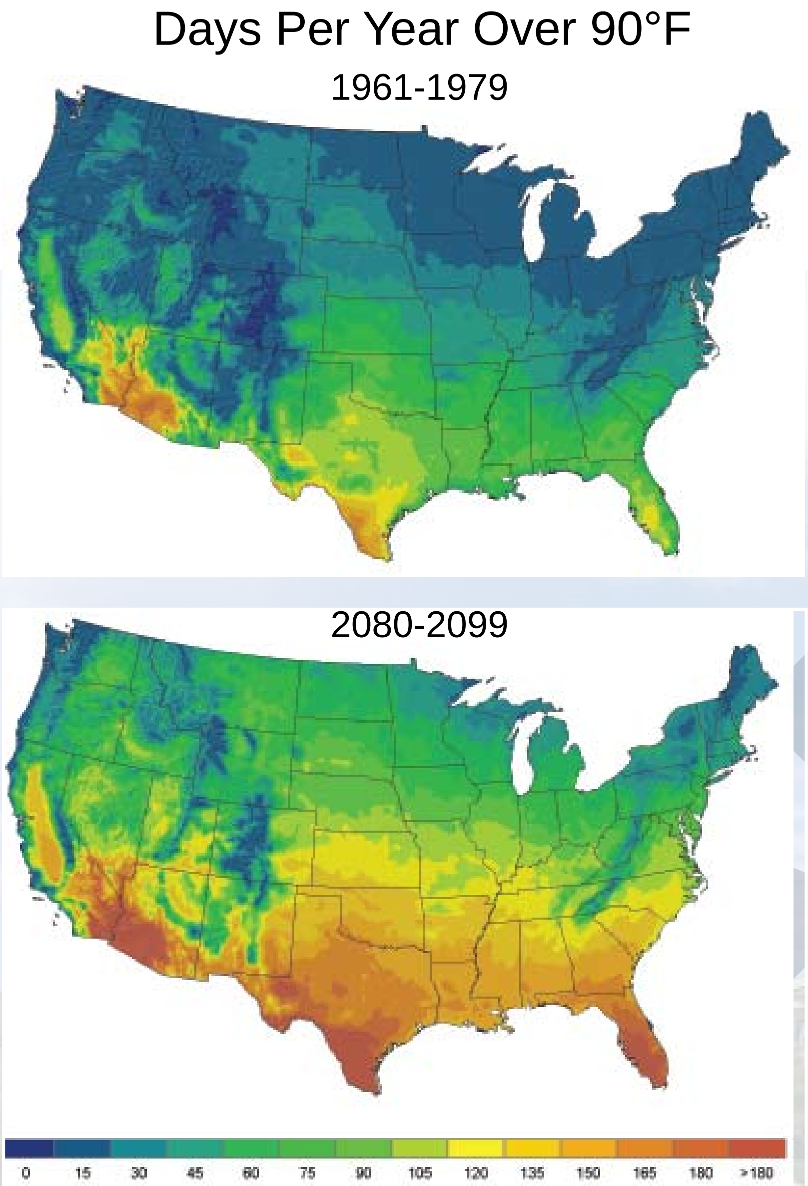
An example of intense precipitation affecting transportation infrastructure was the record-breaking 24-hour rainstorm in July 1996, which resulted in flash flooding in Chicago and its suburbs, with major impacts. Extensive travel delays occurred on metropolitan highways and railroads, and streets and bridges were damaged. Commuters were unable to reach Chicago for up to three days, and more than 300 freight trains were delayed or rerouted[23].

The June 2008 Midwest floods caused I-80 in eastern Iowa to be closed for over five days, disrupting major east-west shipping routes for trucks and the east-west rail lines through Iowa. These floods exemplify the kind of extreme precipitation events and their direct impacts on transportation that are likely to become more frequent in a warming world. These extremes create new and more difficult problems that must be addressed in the design, construction, rehabilitation, and operation of the nation's transportation infrastructure.

Air

Increased delays due to heavy downpours are likely to affect operations. Storm water runoff that exceeds the capacity of collection and drainage systems will cause flooding, delays, and airport closings. Heavy downpours will affect the structural integrity of airport facilities, such as through flood damage to runways and other infrastructure. All of these impacts have implications for emergency evacuation planning, facility maintenance, and safety[26].

The increase in extreme heat will limit some operations and cause pavement and track damage. Decreased extreme cold will confer benefits.



The maps illustrate, for example, that parts of the South that currently see about 60 days per year with temperatures over 90°F (areas in dark green) are projected to experience 150 or more days per year over 90°F (areas in orange) by the end of this century under higher emissions scenarios.

Land

Longer periods of extreme heat in summer may damage roads in several ways including softening of asphalt that leads to rutting from heavy traffic. Sustained air temperature over 90ºF is a significant threshold for such problems. Extreme heat can cause deformities in rail tracks, at minimum resulting in speed restrictions, and at worst, causing derailments. Air temperatures above 100ºF can lead to equipment failure. Extreme heat also causes thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs. Vehicle overheating and tire deterioration are additional concerns[16]. Higher temperatures will also increase refrigeration needs for goods during transport, particularly in the South, raising transportation costs[17a].

Increases in very hot days and heat waves are expected to limit construction activities due to health and safety concerns. U.S. Occupational Safety and Health Administration guidance states that concern for heat stress for moderate to heavy work begins at about 80ºF as measured by an index that combines temperature, wind, humidity, and direct sunlight. For dry climates, such as Phoenix and Denver, National Weather Service Heat Indices above 90ºF may be permissible while higher humidity areas such as New Orleans or Miami should consider 80-85ºF as an initial level for work restrictions[17b].

Wildfires are projected to increase, threatening communities and infrastructure directly and bringing about road and rail closures in affected areas.

In many northern states, warmer winters will bring about reductions in snow and ice removal costs, lessen adverse environmental impacts from the use of salt and chemicals on roads and bridges, extend the construction season, and improve the mobility and safety of passenger and freight travel through reduced winter hazards. On the other hand, more freeze-thaw conditions are projected to occur in northern states, creating frost heaves and potholes on road and bridge surfaces and resulting in load restrictions on certain roads to minimize the damage. With the expected earlier onset of seasonal warming, the period of springtime load restrictions may be reduced in some areas, but it is likely to expand in others with shorter winters but longer thaw seasons. Longer construction seasons will be a benefit in colder locations[18].

Water

Warming is projected to mean a longer shipping season but lower water levels for the Great Lakes and St. Lawrence Seaway. Higher temperatures, reduced lake ice, and increased evaporation are expected to combine to produce lower water levels as climate warming proceeds. With lower lake levels, ships will be unable to carry as much cargo and hence shipping costs will increase. In 2000 and 2001, water levels in the St. Lawrence Seaway were at their lowest point in 35 years, reducing vessel carrying capacity to about 90% of normal. A recent study, for example, found that the predicted reduction in Great Lakes water levels would result in an estimated 13 to 29 percent increase in shipping costs for Canadian commercial navigation by 2050, all else remaining equal.

Navigable Inland Waterways

(see endnote 8)

Lower water levels could also create problems for river traffic, reminiscent of the stranding of more than 4,000 barges on the Mississippi River during the drought in 1988. If low water levels become more common because of drier conditions due to climate change, freight movements in the region could be seriously impaired, and extensive dredging could be required to keep shipping channels open. On the other hand, a longer shipping season afforded by a warmer climate could offset some of the resulting adverse economic effects.

In cold areas, the projected decrease in very cold days will mean less ice accumulation on vessels, decks, riggings, and docks; less ice fog; and fewer ice jams in ports.

Increases in extreme heat will result in payload restrictions and could cause flight cancellations and service disruptions at affected airports.

Air

Rising temperatures will affect airport ground facilities, runways in particular, in much the same way they affect roads. Airports in some areas are likely to benefit from reduction in the cost of snow and ice removal and the impacts of salt and chemical use, though some locations have seen increases in snowfall. Airlines could benefit from reduced need to de-ice planes.

More heat extremes will create added operational difficulties, for example, causing greater energy consumption by planes on the ground. Extreme heat also affects aircraft lift; hotter air is less dense, reducing the lift produced by the wing and the thrust produced by the engine, problems exacerbated at high altitudes and high temperatures. Planes thus need to take off faster, and if runways are not sufficiently long for aircraft to build up enough speed to generate lift, aircraft weight must be reduced. Thus, increases in extreme heat will result in payload restrictions, could cause flight cancellations and service disruptions at affected airports, and could require some airports to lengthen runways. Recent hot summers have seen flights cancelled due to heat, especially in high altitude locations. Economic losses are expected at affected airports. A recent analysis projects a 17% reduction in freight carrying capacity for a single Boeing 747 at the Denver airport by 2030 and a 9% reduction at the Phoenix airport due to increased temperature and water vapor[19].

Drought

Rising air temperatures increase evaporation, contributing to dry conditions, especially when accompanied by decreasing precipitation. Even where total annual precipitation does not decrease, precipitation is projected to become less frequent in many parts of the country[20]. Drought is expected to be an increasing problem in some regions; this, in turn, has impacts on transportation. For example, increased susceptibility to wildfires during droughts could threaten roads and other transportation infrastructure directly, or cause road closures due to fire threat or reduced visibility such as in Florida and California in recent years. There is also increased susceptibility to mudslides in areas deforested by wildfires. Airports could also suffer from decreased visibility due to wildfires. River transport is also seriously affected by drought, with reductions in the routes available, shipping season, and cargo carrying capacity.

Increased intensity of strong hurricanes would lead to more evacuations, damages, transportation interruptions, and a greater probability of infrastructure failure.

More intense hurricanes in some regions are a projected effect of climate change. Three aspects of tropical storms are relevant to transportation: precipitation, winds, and wind-induced storm surge. Stronger hurricanes have longer periods of intense precipitation, higher wind speeds (damage increases with wind speed), and higher storm surge and waves.

Land

There will be a greater probability of infrastructure failures such as highway and rail bridge decks being displaced and railroad tracks being washed away. Storms leave debris on roads and rail lines, which can damage the infrastructure and interrupt travel and shipments of goods. In Louisiana, the Department of Transportation and Development spent $74 million for debris removal alone in the wake of Hurricanes Katrina and Rita. The Mississippi Department of Transportation expected to spend in excess of $1 billion to replace the Biloxi and Bay St. Louis Bridges, repair other portions of roadway, and remove debris. As of June 2007, more than $672 million had been expended.

Adaptation Strategies

Transportation planners have not typically accounted for climate change in their planning horizons or project development. The longevity of transportation infrastructure, the long term nature of climate change, and the potential impacts identified by recent studies warrant serious attention to climate change in planning new or rehabilitated transportation systems.

Planners have generally relied on weather variations of the past as a guide to the future, planning, for example, for a "100-year flood," which may now come much more frequently as a result of climate change. Historical analysis of weather data has thus become less accurate as a forecasting tool. The rapid changes in climate make it more difficult to predict the frequency and intensity of weather events that can influence transportation.

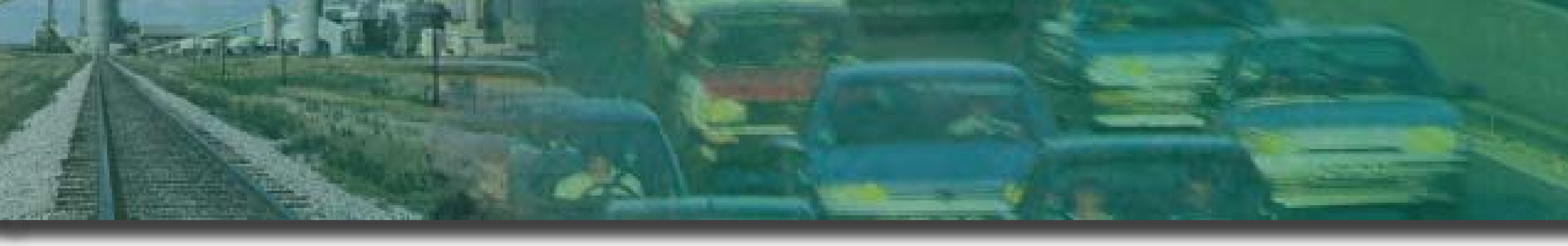
Transportation planners, designers, and operators would be wise to adopt probabilistic approaches to developing transportation projects rather than relying on the deterministic approaches of the past. The uncertainty associated with predicting impacts over a 50- to 100-year time period makes risk management a reasonable approach for realistically incorporating climate change into decision-making and investment.

Lengthening the time frames examined in the transportation planning process is a key element. The 20-year time period required under federal law for highways and transit is not sufficient to encompass the useful life of transportation infrastructure and the risks to which it will be exposed due to climate change.

Strategic examination of national, regional, state, and local networks is an important step toward understanding the risks. Communities can begin by taking inventory of their transportation assets and assessing what needs protection and factoring this into planning, using probabilistic methods. Strategic analysis can also be effective in the design of a project or the planning of a transportation network.

A range of adaptation responses can be employed by transportation professionals to reduce the risks posed by climate change. Infrastructure can be designed to withstand projected impacts or to be protected by natural or manufactured barriers. This can include development of materials and equipment that are more durable or have other desirable characteristics. Efforts can be made to enhance redundancy of critical services. Operational improvements can be developed and implemented. And infrastructure can be relocated or development limited to avoid impacts.

Planning for and adapting to climate change is an evolutionary process. Through adoption of longer planning horizons, risk management, and adaptive responses, vulnerable transportation infrastructure can be made more resilient, maintaining critical services in the face of climate stressors.



There will be more frequent and potentially more extensive emergency evacuations. Damage to signs, lighting fixtures, and supports will increase. The lifetime of highways that have been exposed to flooding is expected to decrease. Road and rail infrastructure for passenger and freight services are likely to face increased flooding by strong hurricanes even by relatively modest storm surges. In the Gulf Coast, more than one-third of the rail miles are likely to flood when subjected to a storm surge of 18 feet[27].

Water

All aspects of shipping are disrupted by major storms. For example, freight shipments need to be diverted from the storm region. Activities at offshore drill sites and coastal pumping facilities would be suspended and extensive damage to these facilities can be expected, as was amply demonstrated during the 2005 hurricane season. Refineries and pipelines are also vulnerable to damage and disruption due to the high winds and storm surge associated with hurricanes and other tropical storms (see *Energy* sector). Barges that are unable to get to safe harbors can be destroyed or severely damaged. Waves and storm surge will damage harbor infrastructure such as cranes, docks and other terminal facilities. There are implications for emergency evacuation planning, facility maintenance, and safety management.

Air

More frequent interruptions in air service and airport closures can be expected. Airport facilities including terminals, navigational equipment, perimeter fencing, and signs are likely to sustain increased wind damage. Airports are frequently located in low-lying areas and can be expected to flood with more intense storms. Eight airports in the Gulf Coast region of Louisiana and Texas are located in historical 100-year flood plains but these events will be more frequent in the future[28].

Spotlight on Hurricane Katrina:

Hurricane Katrina was the most destructive and costliest natural disaster in U.S. history, claiming more than 1800 lives and causing an estimated $134 billion in damage[29, 29a]. It also seriously disrupted transportation systems as key highway and railroad bridges were heavily damaged or destroyed, necessitating rerouting of traffic and placing increased strain on other routes, particularly other rail lines. Replacement of major infrastructure took from months to years. The CSX Gulf Coast line was re-opened after five months and $250 million in reconstruction costs, while the Biloxi-Ocean Springs Bridge took more than two years to reopen. Barge shipping was halted, as was grain export out of the Port of New Orleans, the nation's largest grain export port. The pipeline network was shut down by the loss of electrical power, producing shortages of natural gas and petroleum products. Total recovery costs of the roads, bridges, and utilities as well as debris removal were estimated to cost $15 to 18 billion[30].

Redundancies in the transportation system, as well as the storm timing and track, helped keep the storm from having major or long-lasting impacts on national-level freight flows. For example, truck traffic was diverted from the collapsed bridge that carries highway I-10 over Lake Pontchartrain to highway I-12, which parallels I-10 well north of the Gulf Coast. The primary north-south highways that connect the Gulf Coast with major inland transportation hubs were not damaged and were open for nearly full commercial freight movement within days. The railroads were able to route some traffic not bound directly for New Orleans through Memphis and other Midwest rail hubs. Because New Orleans is not as major a transportation hub as, for example, Houston, given different timing or storm track, the transportation impacts could have been worse.

Hurricane Katrina damage to U.S. Highway Bridge.

Arctic warming reduces sea ice, lengthening the ocean transport season. Permafrost thaw in Alaska damages infrastructure. The ice road season becomes shorter.

Special issues in Alaska

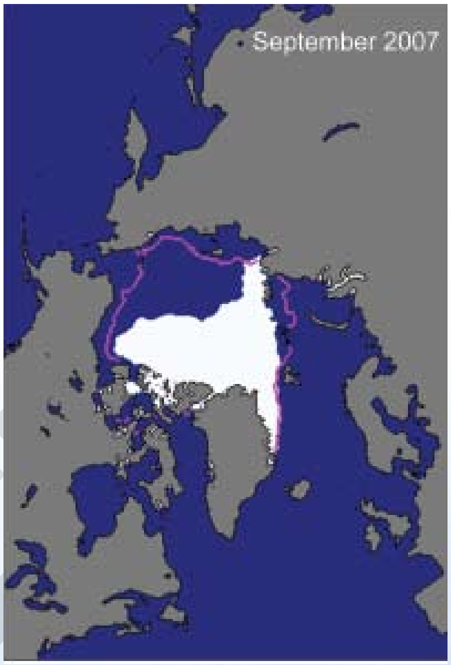
> *Alaska is warming at twice the rate of the rest of the nation, bringing both opportunities and challenges.*

Warming has been most rapid in high northern latitudes. As a result, Alaska is warming at twice the rate of the rest of the nation, bringing both major opportunities and major challenges. Alaska's transportation infrastructure differs sharply from that of the lower 48 states. Although Alaska is twice the size of Texas, its population and road mileage are more like Vermont's. Only 30% of the roads are paved. Air travel is much more common than in other states. Alaska has 84 commercial airports and more than 3,000 airstrips, many of which are the only means of transport for rural communities. Unlike other states, over much of Alaska, the land is generally more accessible in winter, when the ground is frozen and ice roads and bridges are available.

Sea ice decline

The striking thinning and downward trend in the extent of Arctic sea ice is regarded as a considerable opportunity for shippers. Continued reduction in sea ice should result in more ice-free ports, improved access to ports and natural resources in remote areas, and longer shipping seasons. For next several decades, however, warming is likely to result in greater variability in year-to-year shipping conditions and higher costs due to requirements for stronger ships and support systems such as ice-capable ships, icebreaker escorts, and search and rescue support.

Arctic Sea Ice Decline



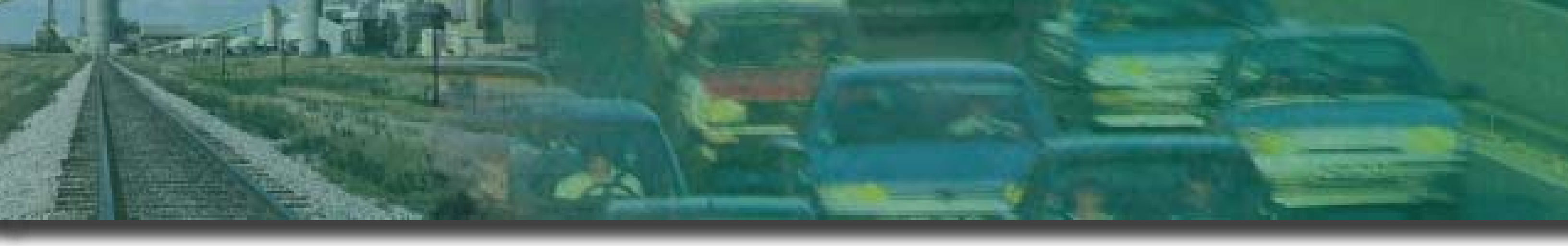
The pink line shows the average September sea ice extent from 1979 through the present. The white area is September 2007 sea ice extent[31].

Over the long term, beyond this century, shippers are looking forward to new Arctic shipping routes, including the fabled Northwest Passage, which could provide significant costs savings in shipping times and distances. However, the next few decades are likely to be very unpredictable for shipping through these new routes. The past three decades have seen very high year-to-year variability of sea ice extent in the Canadian Arctic, despite the overall decrease in September sea-ice extent. And the manner in which ice blockages control ice movement through the channels of the Canadian Archipelago may actually place more icebergs in the shipping channels of the Northwest Passage in the coming decades.

Thawing ground

The challenges warming presents for transportation on land are considerable. For highways, thawing of permafrost causes settling of the roadbed and frost heaves that adversely affect road performance, such as load-carrying capacity. The majority of the state's highways are located in areas where permafrost is discontinuous, and dealing with thaw settlement problems already claims a significant portion of highway maintenance dollars.

Bridges and large culverts are particularly sensitive to movement caused by thawing permafrost and are often much more difficult than roads to repair and modify for changing site conditions. Thus, designing these facilities to take climate change into account is even more critical than is the case for roads. Another impact of climate change on bridges is increased scouring. Hotter, drier summers have led to increased glacial melting and longer periods of high streamflows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments. Temporary ice roads and bridges are commonly used in many parts of Alaska to access northern communities and provide support for the mining



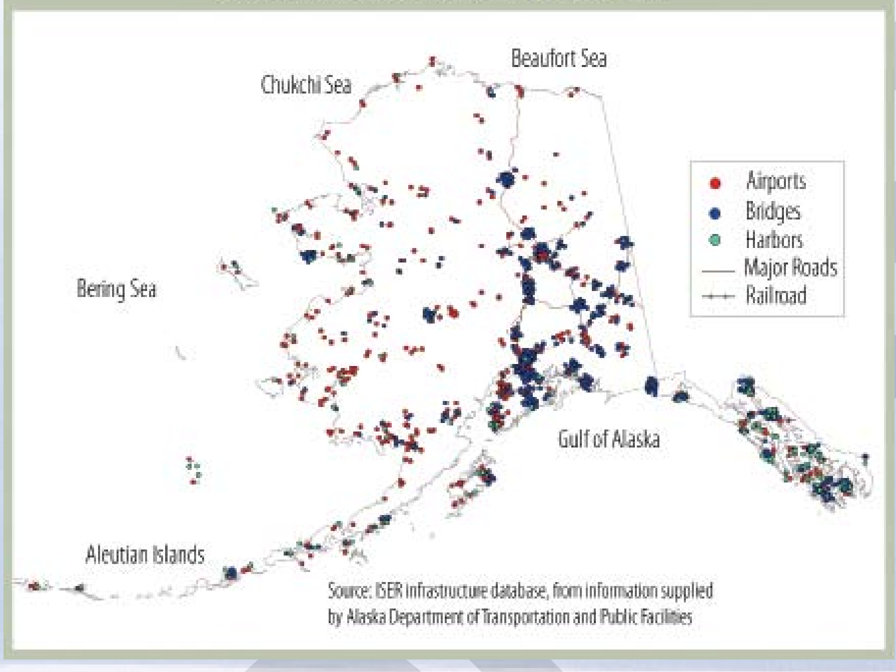
and oil and gas industries. Rising temperatures have already shortened the season during which these critical facilities can be used. Like the highway system, the Alaska Railroad crosses permafrost terrain, and frost heave and settlement from thawing affect some portions of the track, increasing maintenance costs.

A significant number of Alaska's airstrips in the southwest, the northwest, and the interior are built on permafrost. These aitstrips will require major repairs or relocation if their foundations are compromised by thawing.

The cost of maintaining Alaska's public infrastructure is projected to increase 10t o 20 percent by 2030 due to warming, costing the state an additional $4 to 6 billion, with roads and airports accounting for about half of this cost. Private infrastructure impacts were not evaluated[30].

The Trans-Alaska Pipeline System, which stretches from Prudhoe Bay in the north to the ice-free port of Valdez in the south, crosses a wide range of permafrost types and varying temperature conditions. More than half of the 800-mile pipeline is elevated on vertical supports over potentially unstable permafrost. Because the system was designed in the early 1970s on the basis of permafrost and climate conditions of the 1950 to 1970 period, it requires continuous monitoring and some supports have had to be replaced.

Transportation Infrastructure in Alaska, 2006



Source: ISER infrastructure database, from information supplied by Alaska Department of Transportation and Public Facilities

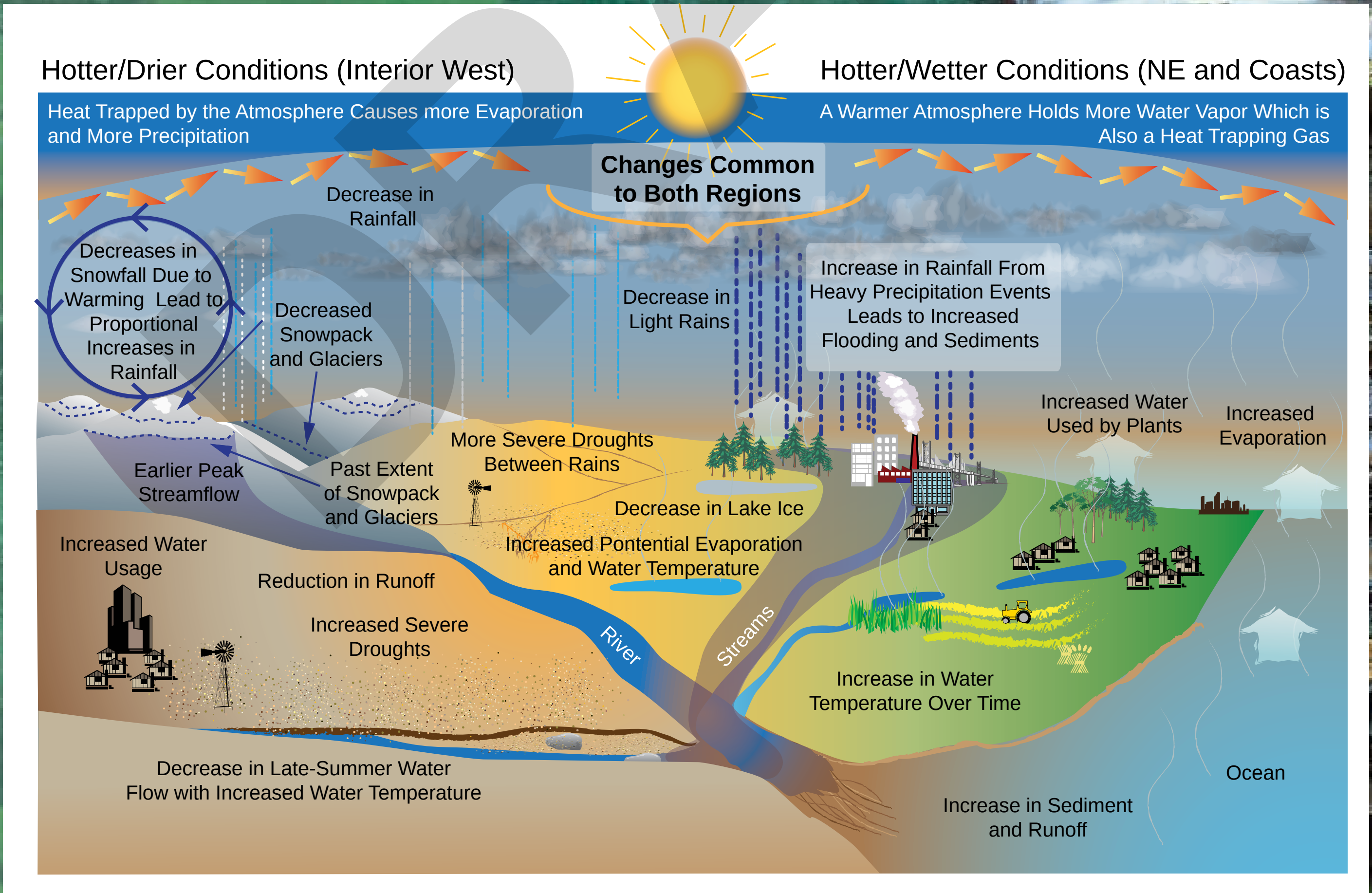
Travel over the tundra for oil and gas exploration and extraction is limited to the period when the ground is sufficiently frozen to avoid damage to the fragile tundra. In recent decades, the number of days that exploration and extraction equipment could be used has dropped from 200 days to 100 days per year due to warming. With warming, the number of exploration days is expected to decline even further.

Water Resources

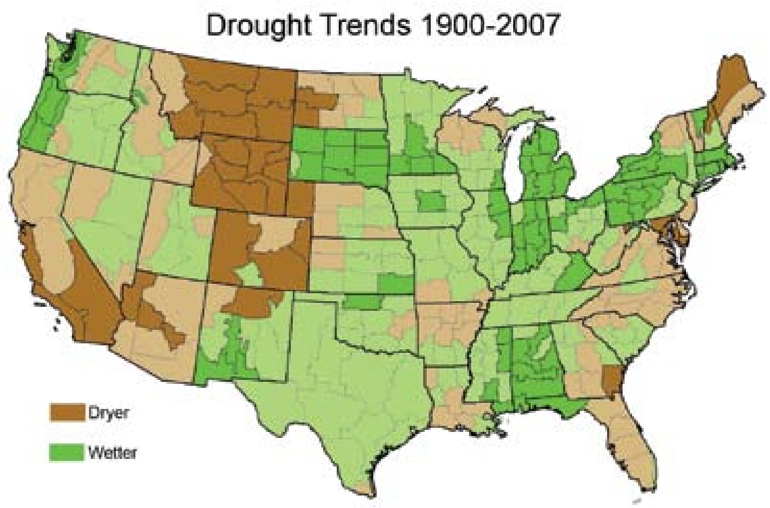
- Climate change will continue to alter the water cycle, affecting where, when, and how much water is available for human and ecosystem uses.
- The quality and quantity of surface water and groundwater are affected by a changing climate.
- Climate change will add yet another burden to already stressed water systems.
- The past century is no longer a reasonable guide to the future for water management.

Nothing is more essential to life and more sensitive to climate change than water. Human society, plants, animals, and ecosystems are all sensitive to variations in the quality, quantity, and timing of water, including precipitation, runoff, and evaporation, as well as the storage of water in glaciers, snow, soil, groundwater, lakes, wetlands, and reservoirs. All of these, in turn, are sensitive to climate change[1].

While climate change affects water, water use also affects climate. A great deal of energy is used to pump, pressurize, treat, transport, and heat water. In planning for the future, it would thus be wise to consider how water supplies will be affected by climate change as well as how water supply choices will influence energy use and therefore climate. For example, one of the options for providing more fresh water is desalination, but this is a very energy intensive process. If energy-intensive water supply options are pursued, it will be important to consider the impact of the chosen energy sources on global climate change.



Climate change will continue to alter the water cycle, affecting where, when, and how much water is available for human and ecosystem uses.



Climate divisions with statistically significant trends are highlighted[22].

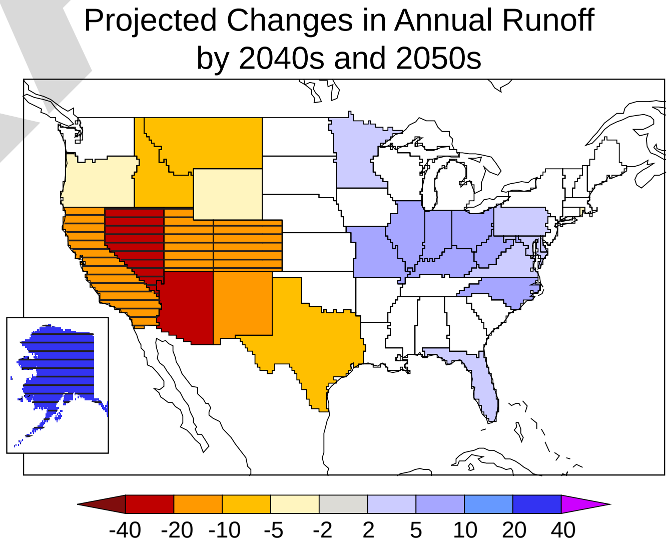
Changes in Timing, Amounts, Types, and Distribution of Precipitation

Substantial changes to the water cycle are expected as the planet warms because water is one of the primary mechanisms used by the Earth for redistributing heat. Evidence is mounting that human-induced climate change is altering many of the existing patterns of precipitation in the United States, including when, where, how much, and what kind of precipitation falls. A warmer climate increases evaporation of water from land and sea, and allows the atmosphere to hold more moisture. For every 1°F rise in global temperature, the water holding capacity of the atmosphere increases by about 4 percent[2]. Coupled with other warming-related changes, this tends to lead to longer and more severe droughts in some areas, especially in arid and semi-arid areas like the Southwest. The additional atmospheric moisture also results in more overall precipitation in some areas, especially in the Northeast and Alaska. Over the past century, precipitation and streamflow have increased in the East and Midwest, with a reduction in drought duration and severity. The West has had reductions in precipitation and increases in drought severity and duration, especially in the Southwest. In most areas of the country, the proportion of rain versus snow has changed to more rain and less snow regardless of changes in overall precipitation during the last 50 years. Despite this general shift from snow to rain, lake effect snowfalls have increased where reduced ice cover leaves open water for evaporation and temperatures are still cold enough to produce heavy snow events. Heavy snowfall has increased in many northern parts of the United States, in contrast to the south where conditions are often too warm and less heavy snow has been observed[4].

While it sounds counterintuitive, a warmer world produces both wetter and drier conditions because even though overall precipitation will increase, the distribution of precipitation will change. More precipitation comes in heavy downpours (which can causing flooding) rather than light events. In the past century, averaged over the U.S., total precipitation has increased by about 7 percent, while the heaviest 1 percent of rain events increased by nearly 20 percent. In addition, observations also show that over the past several decades extended dry periods are becoming more frequent in the eastern and southwestern U.S.[5]. Longer periods between rainfalls, combined with higher air temperatures, dry out soils and vegetation, causing drought.

Changes in Future Runoff Amounts

Runoff, which accumulates as stream flow, is the amount of precipitation that is not evaporated, stored as snowpack or soil moisture, or filtered



Percentage change relative to 1900-1970 baseline. Any color indicates that greater than 66 percent of models agree on the direction of change, *i.e.*, that it is an increase or a decrease; hatching indicates that greater than 90 percent of models agree on this[5a].

Highlights of Impacts by Sector

Sector	Impacts
Human Health	Heavy downpours increase incidence of water-borne diseases and floods resulting in hazards to human life and health.
Energy Production and Use	Reductions in hydropower. Reduced power generation in fossil fuel and nuclear plants due to increased water temperatures and reduced cooling water availability.
Transportation	Floods disrupt transportation. Heavy downpours adversely affect surface and air transportation. Declining Great Lakes levels reduce freight capacity.
Agriculture and Land Resources	Heavy downpours increase soil erosion and can reduce crop yields. Earlier spring snowmelt leads to increased number of fires.
Natural Environment and Biodiversity	Cold water fish threatened by rising water temperatures.

down to groundwater. The proportion of precipitation that runs off is determined by a variety of factors including temperature, windspeed, humidity, sun intensity, vegetation, and soil moisture. Increases and decreases in precipitation do not necessarily lead to equal increases and decreases in runoff. For example, droughts cause soil moisture reductions that can reduce expected runoff until soil moisture is replenished. Thus, water-saturated soils can generate floods with only moderate additional precipitation. Climate models consistently project that the East will experience increased runoff, and moving westward, there will be substantial declines in the Interior West, especially the Southwest. Projections for runoff in California and other parts of the West also show reductions, although less than in the Interior West.

Changes in Snowmelt Dominated Systems

Large portions of the West rely on snowpack as a natural reservoir to hold winter precipitation until it later runs off as streamflow in spring, summer, and fall. Over the last 50 years, there have been widespread temperature-related reductions in snowpack in the West, with the largest reductions occurring in lower elevation mountains in the Pacific Northwest and California where snowfall occurs at temperatures close to the freezing point. Runoff is occurring earlier in the year in snowmelt-dominated areas of the West, in some cases, up to 20 days earlier. Future projections for most snowmelt-dominated basins in the West consistently indicate earlier spring runoff, which produces lower late-summer streamflows[6].

Observed Changes in Water Resources During the Last Century[7]

Event	Increase/ Decrease	Region
1 to 4 Week Earlier Peak Streamflow due to earlier warming-driven snowmelt		West and Northeast
Proportion of Precipitation falling as snow	↓	West
Duration and extent of snow cover	↓	Most of U.S.
Mountain Snow Water Equivalent	↓	West
Annual Precipitation	↑	Most of U.S.
Annual Precipitation	↓	Southwest
Frequency of Heavy Precipitation Events	↑	Most of U.S.
Streamflow	↑	Most of East
Glacier Size or Extent	↓	U.S. Western Mountains, Alaska
Water Temperature of Lakes	↑	Most of U.S.
Ice Cover	↓	Great Lakes
Time between rainfall events	↑	Most of U.S.
Periods of Drought	↑	West, Southeast
Salination of Surface Waters	↑	Florida, Louisiana
Widespread Thawing of Permafrost	↑	Alaska

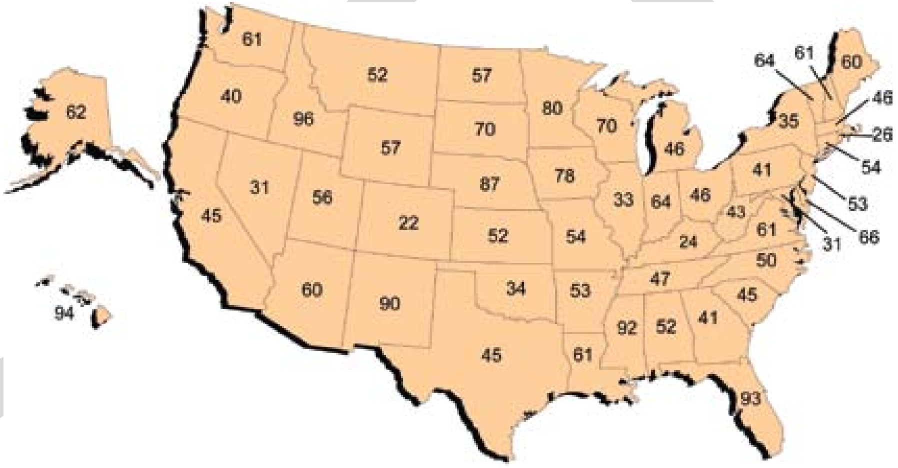
The quality and quantity of surface water and groundwater are affected by a changing climate.

Changes in water quality

Increased air temperatures lead to higher water temperatures, which have already been detected in many streams, especially during low flow periods. In lakes and reservoirs, higher water temperatures lead to longer periods of stratification (when surface and bottom waters don't mix). Dissolved oxygen is reduced in lakes, reservoirs, and rivers at higher temperatures. Oxygen is an essential resource for many living things, and its availability is reduced at higher temperatures both because the amount that can be dissolved in water is lower and because respiration rates of living things are higher. Low oxygen stresses aquatic animals such as cold-water fishe and the insects and crustaceans on which they feed.

Many forms of water pollution including sediments, nitrogen from agriculture, disease pathogens, pesticides, herbicides, salt, and thermal pollution will be made worse by observed and projected increases in precipitation intensity and longer periods when streamflow is low. However, regions that experience increased streamflow will have the benefit of pollution being more diluted. Heavy downpours lead to increased sediment in runoff and outbreaks of water-borne diseases[8]. Increases in pollution carried to lakes, estuaries, and the coastal ocean, especially when coupled with increased temperature, can result in blooms of harmful algae and bacteria.

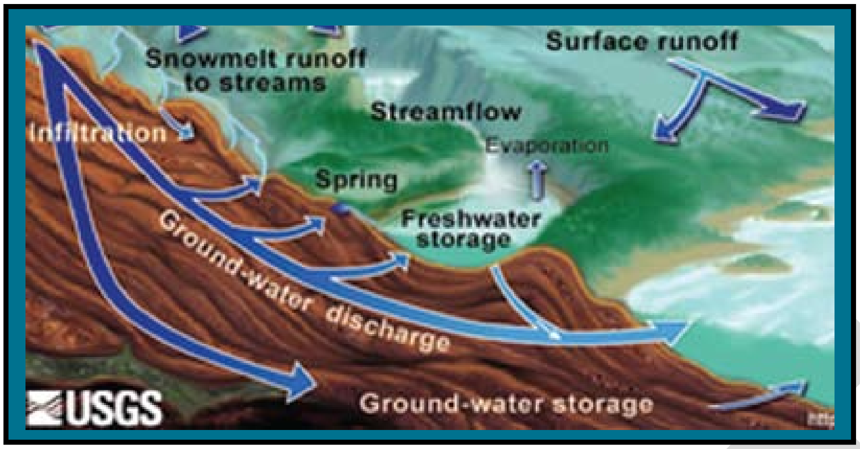
Percent of State Population Using Ground Water as Drinking Water in 1995



Changes in Groundwater

Many parts of the U.S. are heavily dependent on groundwater for drinking and residential water supplies. How climate change will affect groundwater is not well known, but increased water demands by society in regions that already rely on groundwater will clearly stress this resource, which is often drawn down faster than it can be recharged. Changes in the water cycle that reduce precipitation or increase evaporation and runoff would reduce the amount of water available for recharge. Changes in vegetation and soils that occur as temperature changes or due to fire or pest outbreaks are also likely to affect recharge by altering evaporation and infiltration rates. Increased frequency and magnitude of floods are likely to increase groundwater recharge in semi-arid and arid areas where most recharge occurs through dry streambeds after heavy rainfalls and floods.

Sea-level rise is expected to increase saltwater intrusion into coastal freshwater aquifers, making them unusable without desalination. Increased evaporation or reduced recharge into coastal aquifers will exacerbate saltwater intrusion. Shallow groundwater aquifers that exchange water with streams are likely to be the most sensitive part of the groundwater system to climate change[9]. Small reductions in groundwater levels can lead to large reductions in streamflow and increases in groundwater levels can increase streamflow[10]. Further, the interface between streams and groundwater is an important site for pollution removal by micro-organisms. Their activity will change in response to increased temperature and increased or decreased streamflow as climate changes, and this will affect water quality.



Place holder for illustration of ground water, surface water connections

The role of wetlands, streams, and interface zones in water purification

Streams, wetlands, and ecosystems in the riparian zone (bordering rivers and surrounding lakes) play an important role in maintaining water quality, particularly because they remove nitrogen from surface water and groundwater flowing through them[11]. Farmers apply nitrogen fertilizer to enhance crop growth but current agricultural practices tend to deposit more nitrogen than necessary[12]. When it runs off to streams and rivers, and ultimately coastal zones, it can cause blooms of harmful algae and low oxygen conditions[13]. Streams along the way remove nitrogen[14], and riparian zones and the interface between streams and groundwater are particularly active sites of nitrogen removal[15,16]. Streams become much less efficient at removing nitrogen when overloaded[17], and riparian zones and the interface between streams and groundwater lose their capacity to remove nitrogen if they become disconnected from the stream, as is likely to happen under reduced streamflow or increased groundwater withdrawals[18]. Although nitrogen is the best-studied, other pollutants, such as phosphorus and pesticides, will also cause impacts in response to projected changes in climate and the water cycle.

Climate change will add yet another burden to already stressed water systems.

In many places, the nation's water systems are already taxed due to aging infrastructure, population increases, and conflicts between water for recreation, farming, hydropower, and ecosystems. Climate change will add another factor to many existing water management challenges.

Rapid Regional Population Growth

The U.S. population is estimated to have grown by almost 7 percent since the 2000 census to over 300 million. Current Census Bureau projections are for this growth rate to continue, with the national population projected to reach 350 million by 2025 and 419 million by 2050. The highest rates of population growth to 2025 are projected to occur in areas that are at risk for reductions in water supplies due to climate change, such as the Southwest.

Eroded concrete water pipe

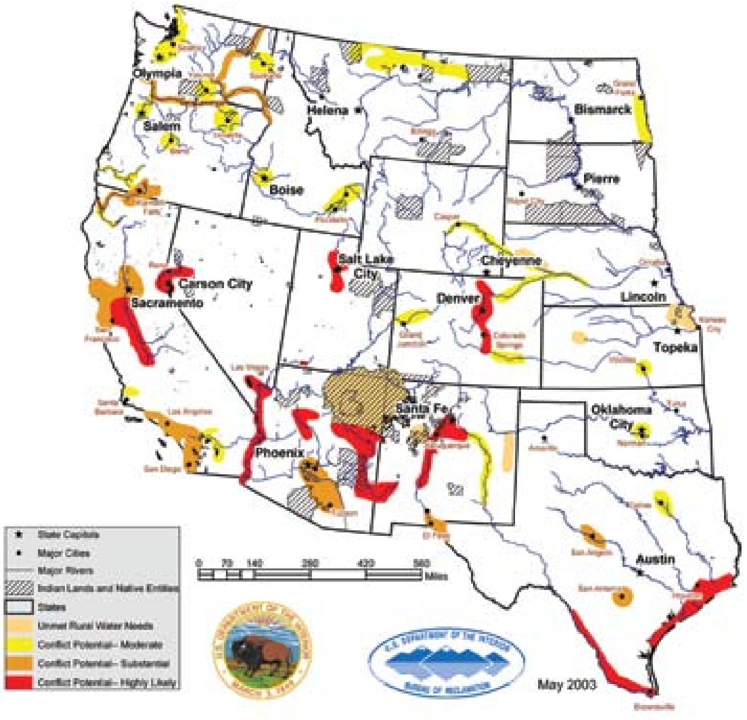
Aging Water Infrastructure

The nation's drinking water and wastewater infrastructure is aging. In older cities, buried water mains can be over 100 years old and breaks of these lines are a significant problem. Sewer overflows resulting in the discharge of untreated wastewater also occur frequently. The Environmental Protection Agency has identified a potential funding shortfall for drinking water and wastewater infrastructure of over $500 billion by 2020. Heavy downpours will exacerbate existing problems in many cities, especially where stormwater catchments and sewers are combined. Drinking water and sewer infrastructure is very expensive to install and maintain. Climate change will present a new set of challenges for designing upgrades to the nation's water delivery and sewage removal infrastructure[19].

Existing Water Disputes throughout the Country

Many locations in the U.S. are already undergoing water stress. The Great Lakes states are working on an interstate compact to protect against reductions in lake levels and potential water exports. Georgia, Alabama, and Florida are in a dispute over water for drinking, recreation, farming, environmental purposes, and hydropower in the Apalachicola-Chattahoochee-Flint system. The State Water Project in California is facing a variety of problems in the Sacramento Delta including endangered species, saltwater intrusion, and potential loss of islands due to flood- or earthquake-caused levee failures. A dispute over endangered fish in the Rio Grande has been ongoing for many years. The Klamath River in Oregon and California has been the location of a multi-year disagreement over native fish, hydropower, and farming. The Colorado River has been the site of numerous interstate quarrels over the last century. By changing the existing patterns of precipitation and runoff, climate change will add another stress to existing problems.

Potential Water Supply Crises by 2025



Areas where existing supplies are not adequate to meet water demands for people, agriculture and the environment.

Spotlight on the Colorado River

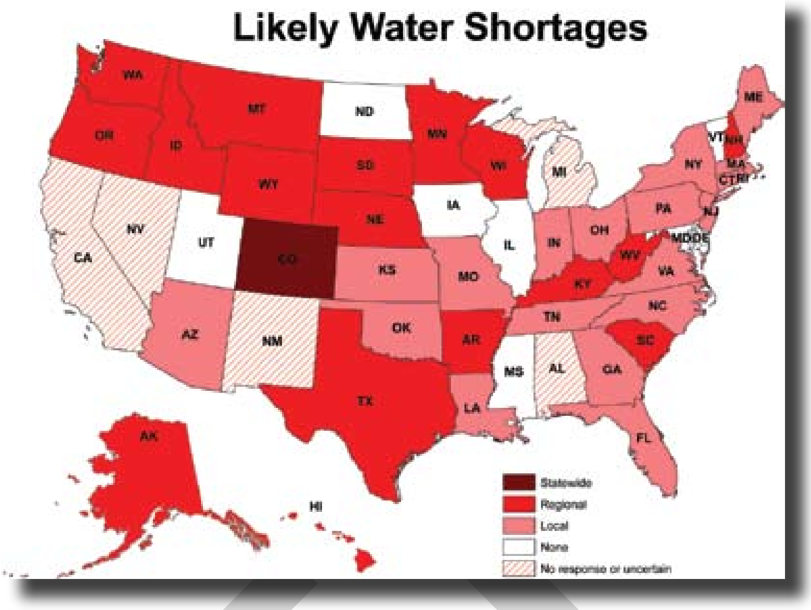
The Colorado River system supplies water to over 30 million people in the Southwest including Los Angeles, Phoenix, Las Vegas, and Denver. Reservoirs in the system, including the giant lakes Mead and Powell, were nearly full in 1999 with almost four times the annual flow of the river stored. By 2007, the system had lost approximately half of that storage after enduring the worst drought in 100 years of record keeping. Runoff was reduced due to low winter precipitation, and warm, dry, and windy springs that substantially reduced snowpack.

Numerous studies over the last 30 years have indicated that the river is likely to experience reductions in runoff due to climate change. In addition, diversions from the river to meet the needs of cities and agriculture are now nearly equal to its average flow. Under current conditions, even without climate change, large year-to-year fluctuations in reservoir storage are possible. If reductions in flow projected to accompany global climate change occur, water managers will be challenged to satisfy all existing demands, let alone the increasing demands of a rapidly growing population[20].

Declines in Lake Powell from June 2002 to December 2003 during a severe drought.

The past century is no longer a reasonable guide to the future for water management.

Water planning has historically been based on the idea that supply and demand would fluctuate within an unchanging envelope of climate variability established by stream gauges and other data collected during the century. Reservoir flood operations, reservoir yields, urban stormwater runoff, and projected water demands are based on these data. Because climate change will significantly modify many aspects of the water cycle, the assumption of an unchanging climate is no longer appropriate for many aspects of water planning. Past assumptions about supply and demand will need to be revisited for existing water projects as well as for proposed projects. New methods for incorporating climate change impacts and the resulting additional uncertainty have been well developed in academic case studies over the past decade or so, but acceptance and use of these experimental methods by water management professionals has, until very recently, been slow to develop.



In 2002 and 2003, the Government Accountability Office conducted a survey of water managers in the 50 states and received responses from 47 states; California, Michigan, and New Mexico did not participate. One of the questions asked of water managers: in the next 1-10 years which, if any, portions of their states are likely to experience water shortages under average water conditions. Managers were instructed to use the last 10-20 years to determine average water conditions, and drought was defined as a deficiency of precipitation, including snow, over several consecutive years[21].

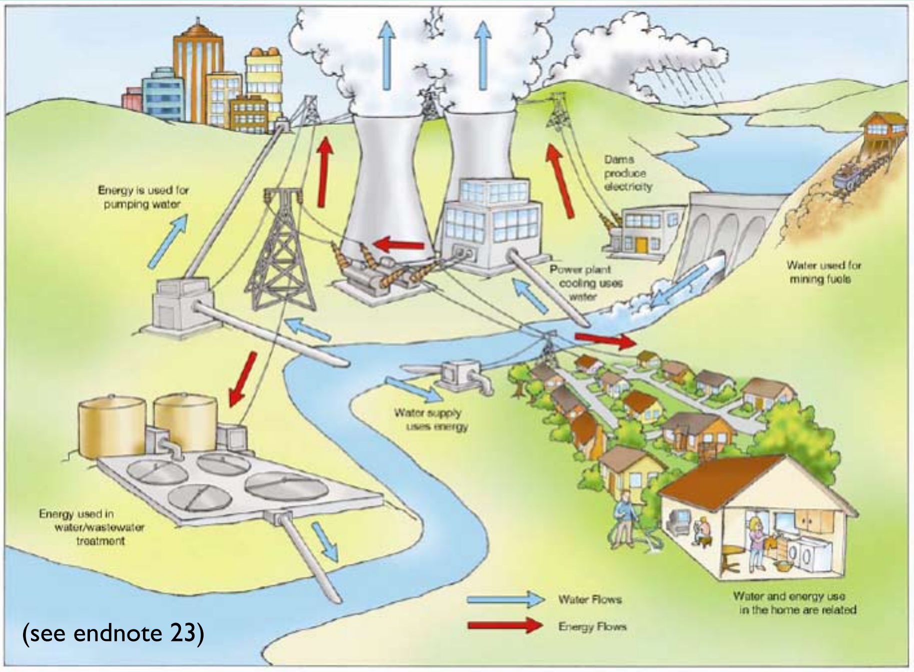
Water systems are now under multiple stresses including a changing climate, population growth, environmental limitations, and competition for limited supplies by agriculture, hydropower, recreation, and municipalities. The intersection of substantial changes in the water cycle along with multiple stresses means that water planning will be doubly challenging. At the same time, many potential adaptations are limited by institutional constraints. Total U.S. water diversions peaked in the 1980s, which implies that expanding supplies to meet new needs will not be a viable option, especially in arid areas likely to experience less precipitation.

Water management has reduced the impacts of significant natural climate variability. The ability to modify operational rules and water allocations is likely to be critical for the protection of infrastructure, for public safety, to ensure reliability of water delivery, and to protect the environment. There are, however, many institutional and legal barriers to such changes in both the short and long term. Four examples:

- The allocation of the water in many interstate rivers is governed by compacts, court decrees, and other agreements that are difficult to modify.
- Reservoir operations are governed by "rule curves" that require a certain amount of space to be saved in a reservoir at certain times of year to capture a potential flood. Developed by the Army Corps of Engineers based on historic flood data, many of these rule curves have never been modified, and modifications may require Environmental Impact Statements.
- In most parts of the West, water is allocated based on a "first in time means first in right" system, and because agriculture was developed before cities were established, large volumes of water typically are allocated to agriculture. Transferring these rights, even for short periods, can involve substantial expense and time and can be socially divisive.
- Changes in forecasting systems and methods are likely to be required to support water management agencies in adapting to climate change, but these processes are not controlled at an institutional level by the water management agencies themselves. High level leadership is required to integrate these activities.

Water and Energy

Water and energy are interconnected. Both are expected to be under increasing pressure in the future and both will be affected by a changing climate. Water is used directly for hydropower, and cooling water is critical for nearly all other forms of electrical power generation (see Energy). Large amounts of energy are needed for pumping, pressurizing, heating, and treating drinking and wastewater. As a result, conserving water has the dual benefit of conserving energy, and potentially reducing greenhouse gas emissions if fossil fuels are the predominant source of that energy. Water managers will increasingly need to consider the energy and related greenhouse gas emission impacts of proposed new water projects.



Water and Energy Connections

(see endnote 23)

Another nexus between water and energy is that planting vegetation can significantly reduce air conditioning costs. However, there is an important trade-off. Places where energy use for cooling is already a substantial cost are often those with water-supply problems. In addition, planting vegetation increases water loss to the atmosphere by plants, thus reducing run-off to streams[21].

Adaptation Strategies

Different areas of the country will face different adaptation challenges. As a result, adaptations will be regionally specific. For example, some areas will need additional storage while others already have substantial storage; some areas will experience predominately wetter conditions with more runoff and floods, while other areas face increases in drought length and severity. No single universal adaptation strategy will work everywhere.

Supply-side adaptations to climate change will involve many traditional techniques including building new surface reservoirs, transferring water from agriculture or other uses, transferring water among basins, and removal of high water-use vegetation, although some of these options carry high environmental and economic costs. Storing water in underground aquifers and desalinizing seawater are considered by some to be useful new techniques, although both involve substantial energy for pumping and treatment. Supply side options may have considerable problems. For example, new reservoirs will have to overcome environmental problems, a lack of good sites, and large expense; water transfers are frequently contentious. Most supply side options involve large capital costs and large new increments of water.

Demand side adaptations for agricultural water use include improved water efficiency measures such as increased reliance on drip irrigation and gray water use. General demand side adaptations include voluntary and mandatory water conservation, various pricing measures (which would require increased installation/use of metering), and the further development of water markets in which water is bought and sold like any commodity and thus shifted to uses that have the highest monetary value. Demand side options are generally less costly, but involve changes in human behavior with unknown results.

Agriculture and

- Crops show mixed responses to lower levels of warming, but higher levels of warming often negatively affect growth and yields.
- Extreme events such as heavy downpours and droughts reduce crop yields.
- Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from rising carbon dioxide (CO_2), increasing stress on crop plants and requiring more pesticide and herbicide use.

- Forage quality in pasture and rangeland generally declines, reducing the land's ability to supply adequate livestock feed.
- Increased heat, disease, and weather extremes reduce livestock productivity.
- Warming and rising CO_2 increase forest growth, but more insect outbreaks, fire, and drought have negative effects.
- Deserts and dry lands become hotter and drier, feeding a self-reinforcing cycle of invasive plants, fire, and erosion.

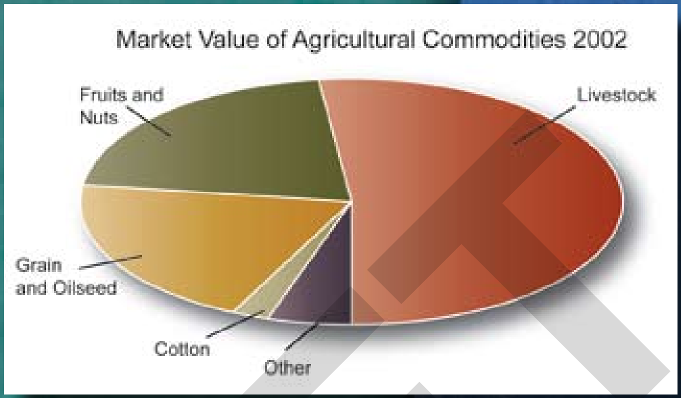
Key Sources

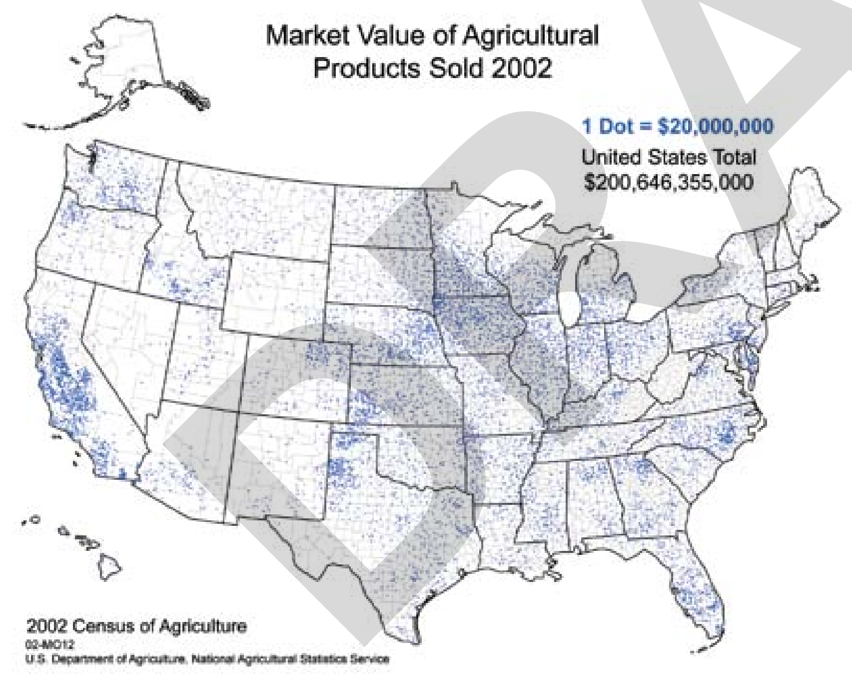
CCSP 3.3 Extremes
CCSP 4.2 Ecosystem Thresholds
CCSP 4.3 Impacts
CCSP 4.4 Ecosystem Adaptation
IPCC WG-1

Land Resources

Agriculture in the United States is extremely diverse and produces over $200 billion a year in food commodities. The impacts of climate change on agriculture will also be very diverse, varying by region and by product[1].

While climate change clearly impacts agriculture, agriculture also impacts climate, contributing 13.5 percent of all human-induced greenhouse gas emissions globally. In the U.S., agriculture represents 8.6 percent of the nation's total greenhouse gas emissions, including 80 percent of its nitrous oxide emissions and 31 percent of its methane emissions[2].



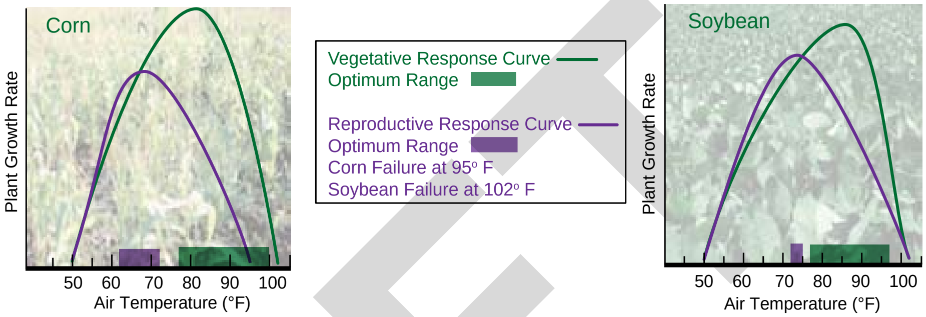


2002 Census of Agriculture
02-M012
U.S. Department of Agriculture, National Agricultural Statistics Service

Crops show mixed responses to lower levels of warming, but higher levels of warming often negatively affect growth and yields.

Crop responses in a changing climate reflect the interplay among three factors: rising temperatures, increasing carbon dioxide concentrations, and changing water resources. Warming causes plants to grow faster, which is not necessarily a good thing, as this means there is less time for the grain to "fill" in cereal crops, reducing their yields[3].

Higher carbon dioxide levels cause plants to grow bigger; again, this is not necessarily a good thing as they are also generally less nutritious with reduced protein content. Carbon dioxide also makes some plants more water-use-efficient, meaning they produce more plant material, such as grain, on less water[4].



Plants need adequate water to maintain their temperature within an optimal range. Without water for cooling, plants will suffer heat stress. In many regions, irrigation water is used to maintain adequate temperature conditions for the growth of cool season plants (such as most vegetables), even in warm environments. With increasing demand and competition for fresh water supplies, the water needed for these crops may be increasingly limited. Variability in the water supply will affect plant growth and cause drastically reduced yields. The amount and timing of precipitation during the growing season are also critical, and will be affected by climate change. Changes in season length are also important and affect crops differently[5].

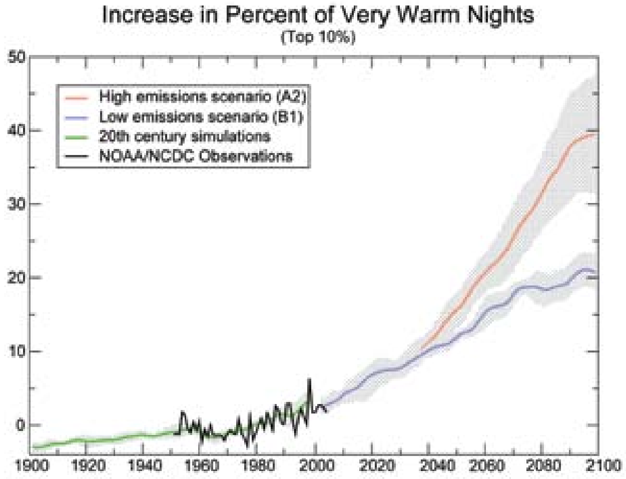
Higher temperatures will mean a longer growing season for crops that do well in the heat, such as melon, okra, and sweet potato, but a shorter growing season for crops more suited to cooler conditions, such as potato, lettuce, broccoli, and spinach[6]. Higher temperatures also cause plants to use more water to keep cool. This is one example of how the interplay between rising temperatures and water availability is critical to how plants respond to climate change. But fruits, vegetables, and grains can suffer even under well-watered conditions if temperatures exceed the maximum level for pollen viability in a particular plant; if temperatures exceed the threshold for that plant, it won't produce seed and so it won't reproduce[7].

The grain-filling period of wheat and other small grains shortens dramatically with rising temperatures. Analysis of crop responses suggests that even moderate increases in temperature will decrease yields of corn, wheat, sorghum, bean, rice, cotton, and peanut crops. Further, as temperatures continue to rise and drought periods increase, crops will be more frequently exposed to temperature thresholds at which pollination and grain-set processes begin to fail and quality of vegetable crops is negatively affected. Grain, soybean, and canola crops have relatively low optimal temperatures, and thus will have reduced yields and will increasingly begin to experience failure as warming proceeds[8].

Some crops are particularly sensitive to high nighttime temperatures, which have been rising even faster than daytime temperatures and are projected to continue to do so[9]. Common snap beans, for example, shows substantial yield reduction when nighttime temperatures exceed 80°F.

Fruits that require long winter chilling periods will suffer declines. Many varieties of fruits (such as popular varieties of apples and berries) require between 400 and 1800 cumulative hours below 45°F each winter to produce good yields the following summer and fall. By late this century, under higher emissions scenarios, winter temperatures in many important fruit-producing regions such as the Northeast will be too consistently warm to meet these requirements. Cranberries have a particularly high chilling requirement and there are no known low-chill varieties. Massachusetts and New Jersey supply nearly half the nation's cranberry crop. By the middle of this century, under higher emissions scenarios, it is unlikely that these areas will provide cranberries with the winter chilling they need[10].

A seemingly paradoxical impact of warming is that it appears to be increasing the risk of plant frost damage. Mild winters and warm, early springs, which are beginning to occur more frequently as climate warms, induce premature plant development and blooming, resulting in exposure of vulnerable young plants and plant tissues to subsequent late-season frosts. For example, the 2007 spring freeze in the eastern United States caused widespread devastation of crops and natural vegetation because the frost occurred during the flowering period of many trees and during early grain development on wheat plants[11]. Another example is occurring in the Rocky Mountains where in addition to the process described above, reduced snow cover leaves young plants unprotected from spring frosts, with some plant species already beginning to suffer as a result[12] (see *Ecosystems* sector).



Change in percent of very warm nights from the 1950 to 1990 average. Under the lower emissions scenario, the percentage of very warm nights increases about 20 percent by 2100 whereas under the higher emissions scenario, it increases by about 40 percent[9].

Effects of increased air pollution on crop yields

Ground-level ozone is an air pollutant that is formed when nitrogen oxides emitted from fossil fuel burning interact with other compounds in the atmosphere[12a] in the presence of sunlight. Higher air temperatures result in greater concentrations of ozone. Ozone at the land surface has risen in rural areas of the United States over the past 50 years, and it is forecast to continue increasing with warming, especially under higher emissions scenarios. Plants are sensitive to ozone, and crop yields are reduced as ozone levels increase. Some crops that are particularly sensitive to ozone pollution include soybeans, wheat, oats, green beans, peppers, and some types of cotton[13].

Extreme events such as heavy downpours and droughts reduce crop yields.

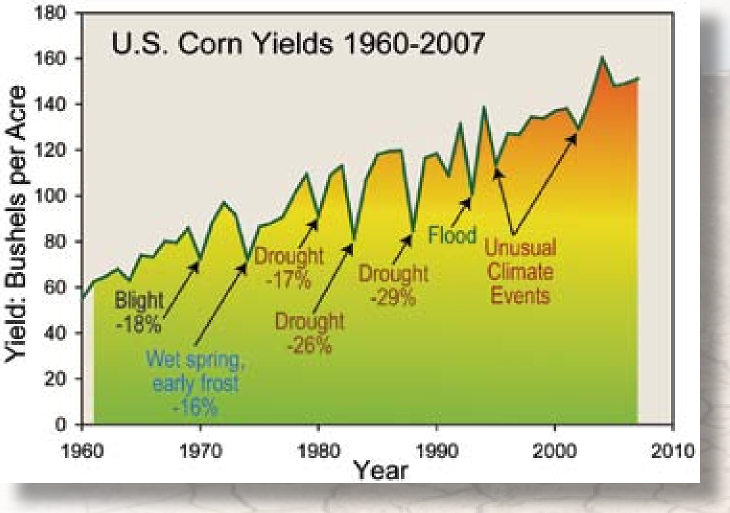
One of the most pronounced effects of climate change is the increase in heavy downpours. Precipitation has become less frequent but more intense, and this pattern is projected to continue across the United States[14]. One consequence of excessive rainfall is delayed spring planting, which jeopardizes profits for farmers paid a premium for early season production of high value crops such as melon, sweet corn, and tomatoes. Field flooding during the growing season causes crop losses due to low oxygen conditions, increased susceptibility to root diseases, and increased soil compaction due to the use of heavy farm equipment on wet soils. In spring 2008, heavy rains caused the Mississippi River to rise to about seven feet above flood stage, putting hundreds of thousands of acres of cropland under water. The flood hit just as farmers were preparing to harvest wheat and to plant corn, soybeans and cotton. The losses have not yet been estimated but are expected to be large, requiring years of recovery time and even putting some farmers out of business. The flooding also caused an increase in runoff and leaching of agricultural chemicals into surface water and groundwater[15].

More rainfall concentrated into heavy downpours also increases the likelihood of water deficiencies at other times because of reductions in rainfall frequency. Another impact of heavy downpours is that wet conditions at harvest time result in reduced quality of many crops. Storm events with heavy rainfall are often accompanied by wind gusts, and both strong winds and rain can flatten crops, causing significant damage. Vegetable and fruit crops are sensitive to even short-term, minor stresses, and as such are particularly vulnerable to weather extremes[16].

Vegetable and fruit crops are sensitive to even short-term, minor stresses, and as such are vulnerable to weather extremes.

Temperature extremes will also pose problems. Even crop species that are well adapted to warmth, such as tomatoes, can have reduced yield and/or quality when daytime maximum temperatures exceed 90°F for even short periods during critical reproductive stages[17]. For many high value vegetable crops, just hours or days of moderate heat stress at critical growth stages can reduce grower profits by negatively affecting visual or flavor quality even when total yield is not reduced[18].

Drought frequency and severity are projected to increase in the future, particularly under higher emissions scenarios[19]. Increased drought will be occurring at a time when crop water requirements are also increasing due to rising temperatures. All crops are negatively affected by water deficits[20].



While technological improvements have resulted in a general increase in corn yields, extreme weather events have caused dramatic reductions in yields in particular years. Increased variation in yield is likely to occur as temperatures increase and rainfall becomes more variable during the growing season. Yields are not expected to continue their historical upward trend as temperatures rise above the optimum for vegetative and reproductive growth.

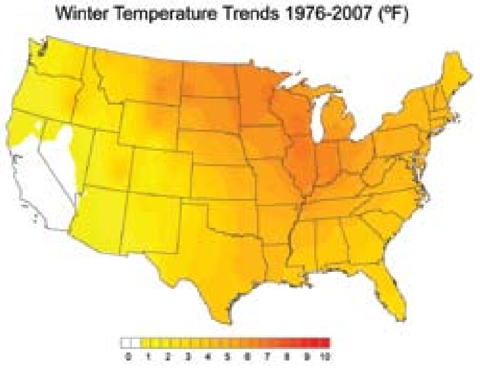
Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from rising carbon dioxide, increasing stress on crop plants and requiring more pesticide and herbicide use.

Weeds benefit more than cash crops from higher temperatures and carbon dioxide (CO_2) levels[21]. One concern with continued warming is the northward expansion of invasive weeds. Southern farmers lose more to weeds than northern farmers. For example, southern farmers lose 64 percent of the soybean crop to weeds while northern farmers lose 22 percent[22]. Some extremely aggressive weeds plaguing the South (such as Kudzu) have historically been confined to areas where winter temperatures do not drop below specific thresholds. As temperatures continue to rise, these weeds will expand their ranges northward into important agricultural areas. Kudzu currently infests 2.5 million acres of the Southeast and is a carrier of the fungal disease soybean rust, which represents a major and expanding threat to U.S. soybean production[23].

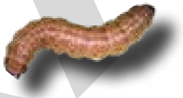
Increasing CO_2 reduces herbicide efficacy[45].

Controlling weeds currently costs the United States more than $11 billion a year, with the majority spent on herbicides[24]; so both herbicide use and costs will likely increase as temperatures and carbon dioxide levels rise. At the same time, the most widely used herbicide in the United States, glyphosate (RoundUp®), loses its efficacy on weeds grown at CO_2 levels that are projected to occur in the coming decades. Higher concentrations of the chemical and more frequent spraying will thus be needed, increasing economic and environmental costs associated with chemical use[25].

Many insect pests and crop diseases thrive due to warming, increasing losses and necessitating greater pesticide use. Warming aids insects and diseases in several ways. Rising temperatures allow both insects and pathogens to expand their ranges northward. In addition, rapidly rising winter temperatures allow more insects to survive over the winter, whereas cold winters once controlled their populations. Some of these insects, in addition to doing direct damage to crops, also carry diseases that harm crops. Crop diseases in general are likely to increase as earlier springs and warmer winters allow proliferation and higher survival rates of disease pathogens and parasites[26]. The longer growing season will allow some insects to produce more generations in a single season, greatly increasing their populations. Finally, plants grown in higher CO_2 conditions tend to be less nutritious, so insects have to eat more to meet their protein requirements, causing greater destruction to crops[27].



Winter temperatures are rising faster than in any other season, especially in many key agricultural regions. This allows many insect pests and crop diseases to expand and thrive, creating increasing challenges for agriculture. This map shows increases of over 7°F in winter temperatures in the Midwest and northern Great Plains over the past 30 years.



As a result of all of these factors, pesticide use will have to increase. Warmer areas already have to spray much more than cooler ones. For example, Florida sweet corn growers spray their fields 15 to 32 times a year to fight pests like corn borer and corn earworm, while New York farmers average only zero to five times. In addition, higher temperatures are known to reduce the effectiveness of certain classes of pesticides (pyrethroids and spinosad).

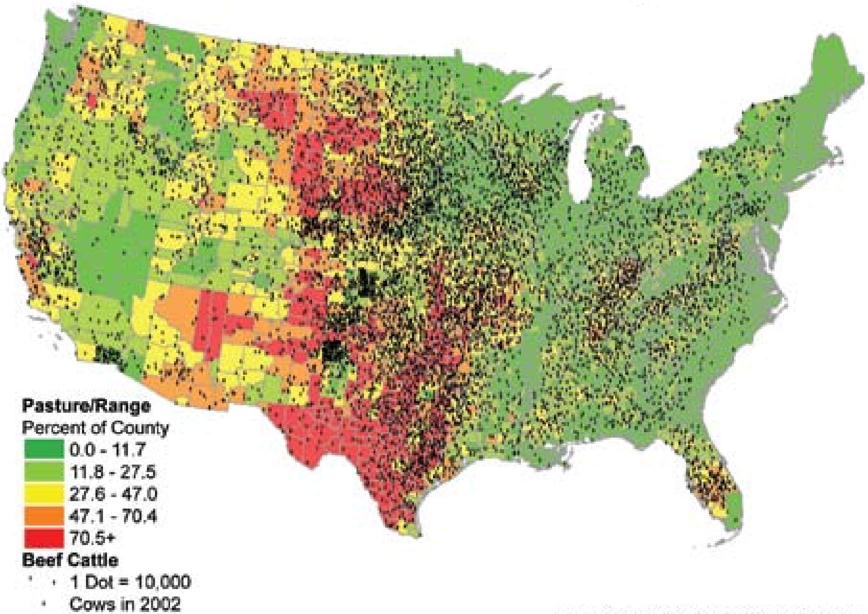
A particularly unpleasant example of how carbon dioxide tends to favor the kinds of plants we'd least like to succeed is found in the response of poison ivy to rising CO_2 concentrations. Poison ivy thrives in air with extra CO_2 in it, growing bigger and producing a more toxic form of the oil, urushiol, that causes painful skin reactions in 80 percent of people. Contact with poison ivy is one of the most widely reported ailments at poison centers in the United States, causing more than 350,000 cases of contact dermatitis each year. The CO_2 growth stimulation of poison ivy exceeds that of most other woody species. Given continued increases in CO_2 emissions, poison ivy is expected to become more abundant and more toxic in the future, with implications for forests and human health[28].

Forage quality in pasture and rangeland generally declines, reducing the land's ability to supply adequate livestock feed. Increased heat, disease, and weather extremes reduce livestock productivity.

Beef cattle production takes place in every state in the United States, with the greatest number raised in regions that have an abundance of native or planted pastures for grazing. Generally, eastern pasturelands are planted and managed, whereas western rangelands are native pastures, which are not seeded and which have much less rainfall. There are transformations now underway in many of these lands as a result of rising atmospheric carbon dioxide levels and the associated climate change, involving which species of grasses dominate, as well as quality changes within species. These changes are generally reducing the quality of the forage, so that more acreage is needed to provide animals with the same nutritional value, resulting in an overall decline in livestock productivity. In addition, woody shrubs and invasive cheatgrass are encroaching into grasslands, further reducing their forage value[30]. The combination of these factors leads to an overall decline in livestock productivity.

Rising atmospheric CO_2 levels impact forage quality because plant nitrogen and protein concentrations often decline with higher concentrations of CO_2[31]. This reduction in protein reduces forage quality and counters the positive effects of CO_2-enrichment on plant production and carbohydrates. Rising CO_2 may also reduce the digestibility of forages that are already of poor quality. Reductions in forage quality could have pronounced negative effects on animal growth, reproduction, and survival, and could render livestock production unsustainable unless animal diets are supplemented with protein, adding more costs to the production. On shortgrass steppe, for example, CO_2 enrichment reduced the protein concentration of autumn forage below critical maintenance levels for livestock in three out of four years and reduced the digestibility of forage by 14 percent in mid-season and by 10 percent in autumn. Significantly, the grass type that thrived the most under excess CO_2 conditions also had the lowest protein concentration[32].

Distribution of Beef Cattle & Pasture/Rangeland



Source: NRCS, 1997 NRI; NASS, 2002 Census of Agriculture

At the scale of a region, the composition of forage plant species is determined mostly by climate and soils. The primary factor controlling the distribution and abundance of plants is water: both the amount of water plants use and water availability over time and space. The ability to predict vegetation changes at local scales and over shorter periods is limited because at these scales the response of vegetation to global-scale changes depends on a variety of local processes including the rate of disturbances such as fire and grazing, and the rate at which plant species can move across sometimes-fragmented landscapes. Nevertheless, some general patterns of vegetation change are beginning to emerge. For example, it has been observed that increasing CO_2 favors weeds and invasive plant species over native species because invasive species have traits (rapid growth rate, prolific seed production) that allow a larger growth response to CO_2. In addition, the effect of increasing CO_2 on plant species composition appears to be greatest where the land has been disturbed (such as by fire or grazing) and nutrient and light availability are high[33].

Heat stress

Like human beings, cows, pigs, and poultry are warm-blooded animals that are sensitive to heat. In terms of production efficiency, studies show that the negative effects of hotter summers will outweigh the positive effects of warmer winters. The more U.S. climate warms, the more production will fall. For example, an analysis of warming in the range of 9 to 11ºF (as projected under higher emissions scenarios) projected a ten percent decline in livestock yields in cow/calf and dairy operations in Appalachia, the Southeast including the Mississippi Delta, and southern Plains regions, while a warming of 2.7ºF caused less than a one percent decline. Temperature and humidity interact to cause stress in animals, just as in humans; the higher the heat and humidity, the greater the stress and discomfort, and the larger the reduction in the animals' ability to produce milk, gain weight, and reproduce. Milk production declines in dairy operations, the number of days it takes for cows to reach their target weight grows longer in meat operations, conception rate in cattle falls, and swine growth rates decline due to heat. As a result, swine, beef and milk production are all projected to decline in a warmer world[34].

Temperature and humidity interact to cause stress in animals, just as in humans.

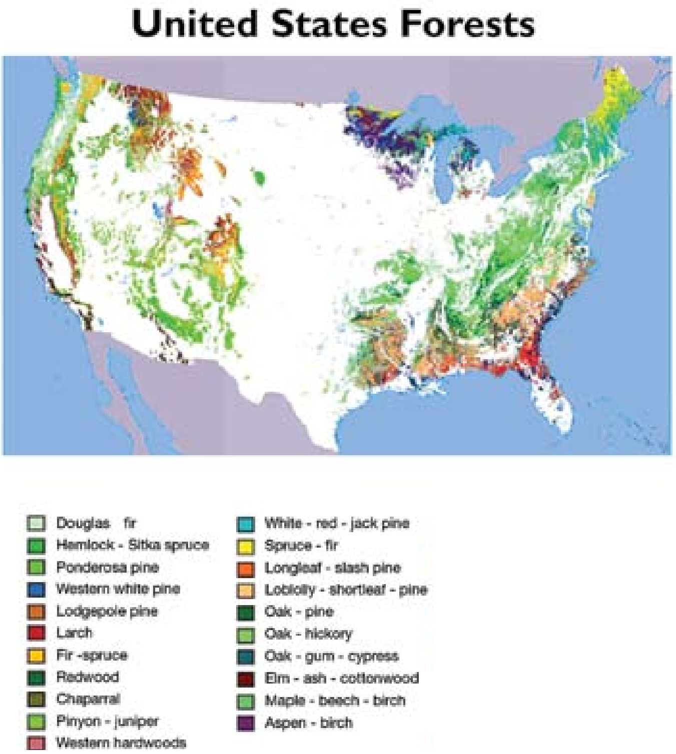
Models project that increases in air temperatures in the central United States could create summer-time losses up to an estimated $93.3 million dollars per year by 2040 as a result of reductions in performance associated with lower feed intake and increased maintenance energy requirements. These losses do not account for the costs of increased death of livestock associated with extreme weather events such as heat waves. Costs of each event can exceed $25 million. Nighttime recovery is an essential element of survival when livestock are stressed by extreme heat. A feature of recent heat waves is the lack of nighttime relief. Large numbers of deaths have occurred in recent heat waves, with individual states reporting losses of 5000 head of cattle in a single heat wave in one summer[35].

Warming can also affect parasites and disease pathogens. The earlier arrival of spring and warmer winters allow greater proliferation and survival of parasites and disease pathogens. In addition, changes in rainfall distributions are likely to lead to changes in diseases sensitive to moisture. Heat stress reduces animals' ability to cope with other stresses, such as diseases and parasites. In addition, changes in rainfall distributions could lead to changes in diseases sensitive to relative humidity.

Warming and rising carbon dioxide increase forest growth, but more insect outbreaks, fire, and drought have negative effects.

Forests cover about 740 million acres of the United States, about one-third of the nation. While occurring in every State, forests are most prevalent in the humid eastern United States, the West Coast, at higher elevations in the interior West and Southwest, and along river corridors in the plains states. Forests provide many services important to the wellbeing of Americans: water quality, water flow regulation and watershed protection; wildlife habitat and biodiversity conservation; recreational opportunities and aesthetic and spiritual fulfillment; raw materials for wood and paper products; climate regulation, carbon storage, and air quality. A changing climate will alter forests and the services they provide; most of these changes are likely to be detrimental.

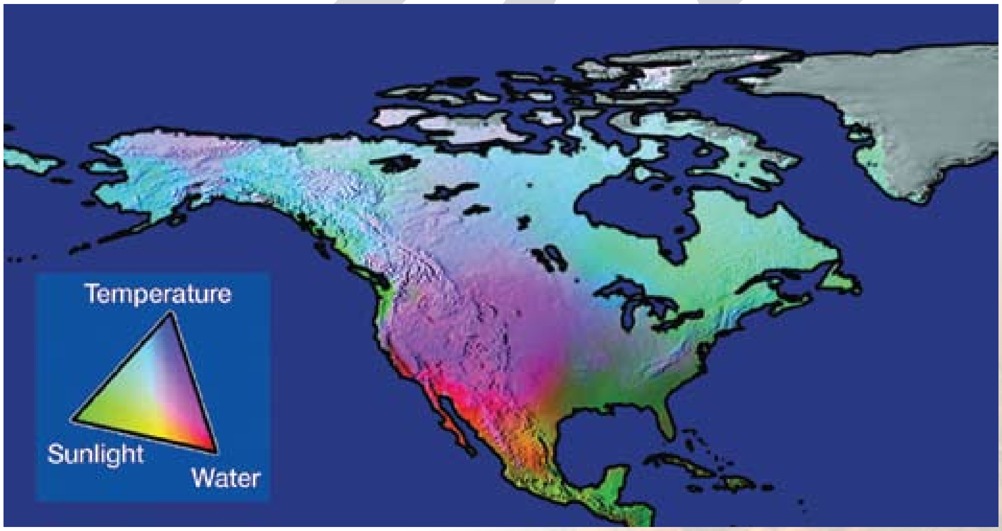
In general, tree growth and productivity increase with rising temperatures and carbon dioxide levels if sufficient amounts of water and nutrients are available. Therefore, forest productivity is projected to increase in much of the East while decreasing in much of the West where water is scarce and projected to become more so. Wherever droughts increase, forest productivity will decrease and tree death will increase. In addition to occurring in much of the West, these conditions are projected to occur in Alaska and in the eastern part of the Southeast.



Distribution of forests in the continental United States by forest type[44].

Disturbances

Besides drought, other major forest disturbances include fires, insect outbreaks, and damage due to severe storms including hurricanes and ice storms. Disturbances are a necessary and natural part of forests, but they are now increasing as a result of human-induced climate change. Disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons.



Potential limits to vegetation productivity based on fundamental physiological limits by sunlight, water balance, and temperature. Nutrients are also important and vary locally[46].

Fire

In the western United States, both the frequency of large wildfires and the length of the fire season have increased substantially in recent decades, due to earlier spring snowmelt and high spring and summer temperatures[36]. These changes in climate have reduced the availability of moisture, drying out the vegetation that provides the fuel for fires. Alaska has also experienced large increases in fire, with the area burned doubling in recent decades[37]. As in the western United States, air temperature is a key predictor of area burned with higher summer air temperatures causing an increase in area burned[38]. In Alaska, for example, June air temperatures alone explained approximately 38 percent of the increase in annual burned area during 1950 to 2003[39].


Ponderosa pine forest after the Hayman fire in Colorado (US Forest Service Photo).

The increase in fires releases more carbon dioxide and soot, creating a feedback loop or cycle in which more warming causes more fires which result in more warming. In addition, increases in fires in Alaska and Canada have consequences for air quality in the central and eastern United States because winds often transport air pollution, including particulates and ground-level ozone, to the south.

Insects

Rising temperatures increase insect outbreaks in a number of ways. First, warmer winters allow larger populations of insects to survive the cold season that normally limits their numbers. Second, the longer warm season allows them to develop faster, sometimes completing two life cycles instead of one in a growing season. Third, warmer conditions help expand their ranges northward. And fourth, drought stress reduces trees ability to resist insect attack, for example, by pushing back against boring insects with the pressure of their sap. Spruce beetle, pine beetle, spruce budworm, and woolly adelgid (which attacks eastern hemlocks) are just some of the insects that are proliferating in the United States, causing devastation in many forests. These outbreaks are projected to increase with ongoing warming. Trees killed by insects also provide more dry fuel for wildfires.

Storms

Intense storms can cause enormous damage to forests creating feedbacks to climate. For example, Hurricane Katrina killed or caused severe structural damage to about 320 million large trees. As these trees decompose over the next few years, they will release an amount of carbon to the atmosphere equivalent to the total carbon taken up in a year by all U.S. forests[40].

Before and after Hurricane Katrina: satellite images of Gulf Coast forests show live trees in green and dead trees in red (Landsat 5 image, source: USGS).

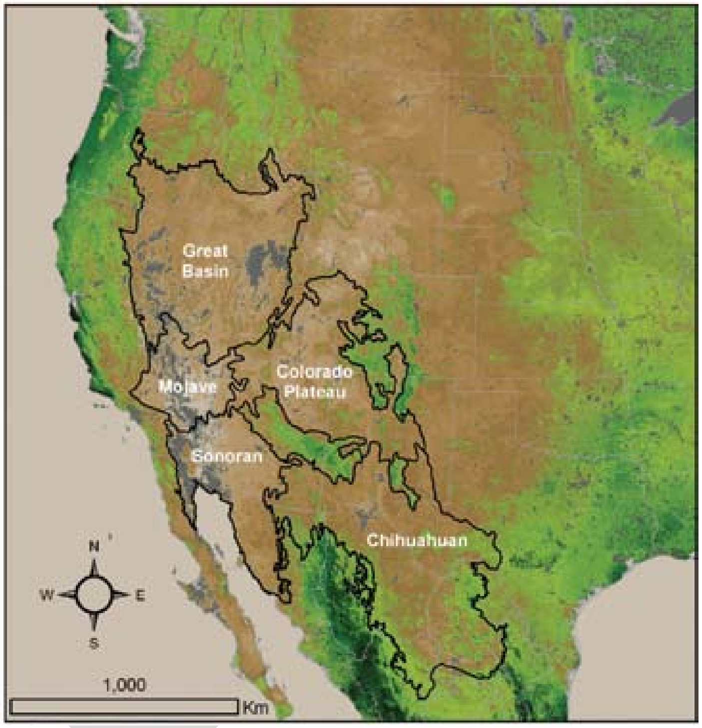
Deserts and dry lands become hotter and drier, creating a self-reinforcing cycle of invasive plants, fire, and erosion.

Forests and carbon storage

Forests in the United States currently offset about 20 percent of our nation's annual fossil fuel carbon emissions. This carbon "sink" is an enormous service provided by forests and its persistence or growth will be important to limiting atmospheric carbon dioxide concentrations. The scale of the challenge of increasing this sink is very large. To offset an additional 10 percent of the U.S. emissions through tree planting would require converting one-third of current croplands to forests [41].

Higher temperatures, increased drought, and more intense thunderstorms increase erosion and promote invasion by non-native grasses.

The arid region of the American Southwest is projected to become drier in this century. There is emerging evidence that suggests that these changes are already underway. Deserts in the United States are also projected to expand to the north, east and upward in elevation in response to projected warming and associated changes in climate.

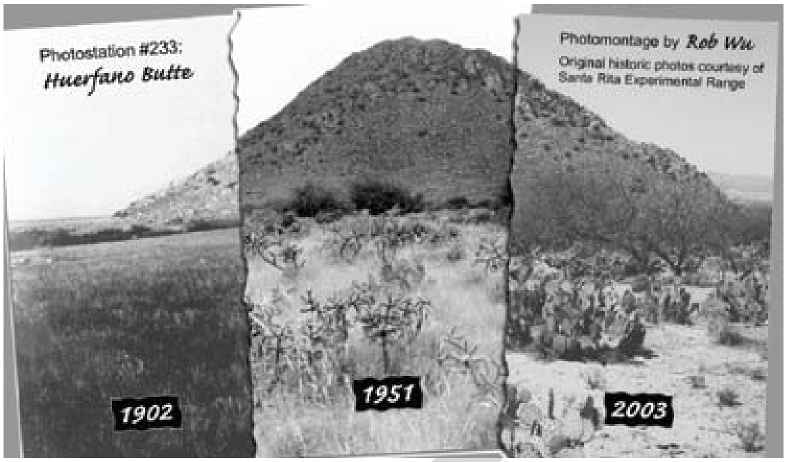


The five major North American deserts[I].

Increased drying in the region contributes to a variety of changes that exacerbate a cycle of desertification. Increased drought conditions cause perennial plants to die due to water stress and increased susceptibility to plant diseases. At the same time, non-native grasses have invaded the region. As these grasses increase in abundance, they provide more fuel for fires, causing fire frequency to increase in a self-reinforcing manner that leads to further losses of vegetation. When it does rain, the rain tends to come in heavy downpours, and since there is less vegetation to protect the soil, water erosion increases. Higher air temperatures and decreased soil moisture reduce soil stability, further exacerbating erosion. And with a growing population needing water for urban uses, hydroelectric generation, and agriculture, there is increasing pressure on mountain water sources that would otherwise flow to desert river areas[42].

The response of arid lands to climate change also depends on how other factors interact with climate at local scales. Large-scale, unregulated livestock grazing in the late 1800s and early 1900s in the Southwest is widely regarded as having contributed to widespread

desertification. Grazing peaked around 1920 on public lands in the West, and by the 1970s it had been reduced by about 70 percent. But arid lands are very slow to recover from the impacts of livestock grazing. Warmer and drier climate conditions are expected to further slow recovery. In addition, the land resource in the Southwest is currently managed more for providing water for people than for protecting the productivity of the landscape. As a result, the land resource is further degraded and recovery hampered[43].



Changes over the 100-year period are the result of grazing management and reduced rainfall in the region.

Adaptation Strategies for Agriculture

Change Planting Date: This can be an effective, no- or low-cost option for taking advantage of a longer growing season or avoiding crop exposure to adverse climatic conditions such as high temperature stress or low rainfall periods. Effectiveness will depend on the region and the rate and amount of warming. It is unlikely to be effective if the farmer goes to market when the supply/demand balance drives prices down. Predicting the optimum planting date for maximum profits will be very challenging in a future with increased uncertainty regarding climate effects on not only local productivity, but also on supply from competing regions.

Change Crop Varieties: Varieties with improved tolerance to heat or drought, or adapted to take advantage of a longer growing season, will be available for some crops. This is less likely to be cost-effective for perennial crops, where changing varieties is extremely expensive and new plantings take several years to reach maximum productivity. Even for annual crops, changing varieties is not always a low-cost option. Seed for new stress-tolerant varieties can be expensive, and new varieties often require investments in new planting equipment, or require adjustments in a wide range of farming practices. In some cases, genetic tolerance to elevated temperature may be difficult to breed for, and it may not be possible to identify an alternative variety that is adapted to the new climate and to local soils and practices, and also meets local market demands.

Change Crop or Livestock Species: This is a much more extreme, high-risk, and in most cases, high-cost option than changing crop varieties. While it could bring new and even increased profits in the long term, it requires the capital to essentially enter into a new business. Accurate predictions of climate trends, and development of the infrastructure and market for the new crops or livestock products would be essential to making this an effective response.

Modify Livestock Facilities: Maintaining livestock production would require modifying facilities to reduce heat stress on animals, using the best understanding of both the chronic and acute stresses that livestock will encounter to determine the optimal modification strategy.

Changes in Water, Fertilizer, Herbicide, and Pesticide Use: Higher temperatures, longer growing seasons, and increased drought will lead to increased agricultural water use in some areas. Obtaining the maximum "carbon dioxide fertilization" benefit often requires more efficient use of water and fertilizers that better synchronizes plant demand with supply. Farmers are likely to respond to more aggressive and invasive weeds, insects, and pathogens with increased use of herbicides, insecticides, and fungicides. Where increases in water and chemical inputs become necessary, this will increase costs for the farmer, as well as having society-wide impacts by depleting water supply, increasing reactive nitrogen and pesticide loads to the environment, and increasing risks to food safety and human exposure to pesticides.

Natural Environment and Biodiversity

- **Ecosystem processes have been affected by climate change.**
- **There have been large-scale shifts in species ranges, the timing of the seasons, and animal migration; further such changes are projected.**
- **There have been increases in fire, insect pests, disease pathogens, and invasive weed species; more such increases are projected.**
- **Coastal and near-coastal ecosystems, including wetlands and coral reefs, are especially vulnerable to the impacts of climate change.**
- **Mountain species and cold-water fish such as salmon and trout are particularly sensitive to climate change impacts.**
- **Arctic sea-ice ecosystems are extremely vulnerable to warming.**

In addition to food, fiber, and other goods that are bought and sold in economic markets, the natural functioning of the environment provides many services on which our society depends. For example, natural ecosystems store carbon in living tissues and in soils, they regulate water flow and water quality, and they stabilize local climates, among many other services. Ecosystem processes are the underpinning of these services: photosynthesis, the process by which plants capture carbon dioxide from the atmosphere and create new growth; the plant and soil processes that recycle nutrients from decomposing matter and maintain soil fertility; and the processes by which plants draw water from soils and return water to the atmosphere. These ecosystem processes are affected by climate and by the concentration of carbon dioxide in the atmosphere.

The diversity of living things, or biodiversity, in ecosystems is itself an enormously important resource that maintains the ability of these systems to provide the services upon which we depend. Many factors affect biodiversity, including: climatic conditions; the presence of competitors, predators, parasites, and disease; disturbance from fire; and other physical factors. Human-induced climate change, in conjunction with other stresses, is beginning to exert major influences on natural environments and biodiversity, and these influences are generally expected to grow with increased warming.

Ecosystem processes have been affected by climate change.

Climate has a strong influence on the processes that control growth and development in natural ecosystems. Examples include how fast plants grow, how rapidly the cycling of nutrients occurs, and whether the carbon captured from the atmosphere and used for plant growth exceeds or is lower than the amount that is released to the atmosphere. Several trends are already evident in natural ecosystems on land in the United States. The growing season is lengthening as a consequence of higher temperatures occurring earlier in the spring. Forest growth has risen over the past several decades as a consequence of a number of factors – young forests reaching maturity, increased concentrations of carbon dioxide in the atmosphere, a longer growing season, increased deposition of nitrogen from the atmosphere – whose individual effects are difficult to disentangle.

At the same time, there have been increases in the size, frequency, and intensity of disturbances – fire and insect infestations being the most visible – that are clearly responding to changes in climate as one of several causal factors. There have also been episodes of extensive death of trees in response to continued extreme drought, especially in the already arid Southwest. There is clear evidence from observations in many different forests that long-term reductions in water availability can increase tree death as well as change the types of species that are able to survive in currently forested areas of the country.

While higher carbon dioxide (CO_2) concentrations cause trees to capture more carbon from the atmosphere, it turns out that they use very little of this extra carbon to produce new wood. The growth effect of extra CO_2 is thus relatively modest, and generally is seen most strongly in young forests on already fertile soils (with enough nitrogen available to enable more growth to occur), and where there is also sufficient water to sustain this growth.

Thus, in the future, as atmospheric CO_2 continues to rise, and as climate continues to change, some forest growth is projected to increase, but only in relatively young forests on fertile soils. The combined effects of increased temperature, increased CO_2, nitrogen deposition, and surface ozone pollution are very difficult to disentangle without substantially more experimentation and improvements in ecosystem models.

There have been large-scale shifts in species ranges, the timing of the seasons, and animal migration; further such changes are projected.

Animal and plant habitats are changing

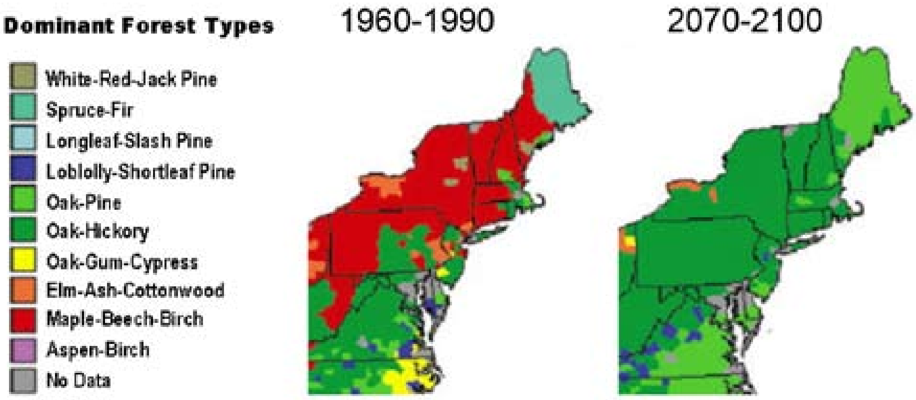
Climate change is already having impacts on animal and plant species throughout the United States. Some of the most obvious changes are related to the timing of the seasons: when plants bud in spring, when birds and other animals migrate, and so on. In the United States, spring now arrives an average of ten days to two weeks earlier than it did 20 years ago. The growing season is lengthening over much of the continental United States. Many migratory bird species are arriving earlier. For example, a study of northeastern bird species that are long-distance migrants found that birds wintering in the southern United States now arrive back in the Northeast an average of 13 days earlier than during the first half of the last century, while birds wintering in South America arrive an average of four days earlier[1].

Another major change is in the geographic distribution of species. Many species in the United States have shifted their ranges northward and upward in elevation. For example, many butterfly species have expanded their ranges northward, contracted the southern parts of their ranges, and shifted to higher elevations as warming has proceeded. A study of Edith's Checkerspot Butterfly showed that 40 percent of the populations below 2400 feet have gone extinct, despite the availability of suitable habitat and food supply. The Checkerspot's most southern populations have also gone extinct, while new populations have been established north of the previous northern boundary for the species[2].

For butterflies, birds and other species, one of the concerns with such changes in geographic range and timing of migration is the potential for mismatches between species and the resources they need to survive. Add to that the rapidly changing landscape (for example, if a species tries to shift northward with the changing climate but there's now a highway or a shopping mall on their new desirable location) and the potential for losses grows. Failure of synchronicity between butterflies and the resources they need led to population extinctions of the Checkerspot Butterfly during extreme drought and low-snowpack years in California.

Tree species are also expected to shift their ranges northward and upslope in response to climate change, although specific quantitative predictions are very difficult to make because of the complications of human land use and many other factors. This would result in major changes in the character of U.S. forests and the types of forests that will be most prevalent in different regions. In the United States, some common forests types are projected to expand, such as oak-hickory. Others are projected to contract, such as maple-beech-birch. Still others, such as spruce-fir, are likely to disappear from the United States altogether[3].

In Alaska, vegetation changes are already underway due to warming. The treeline is shifting northward into tundra, encroaching on the habitat for many migratory birds and land animals like caribou that depend on the open tundra landscape.



The maps show current and projected forests types for the Northeast. Note that Maple-Beech-Birch, currently a dominant forest type in the region, could be completely displaced by other forest types in a warmer future[1].

As warming drives changes in timing and geographic ranges for various species, it is important to note that entire communities of species do not shift intact. Rather, the range and timing of each species shifts in response to its sensitivity to climate change, its mobility, its lifespan, and the availability of the resources it needs (like soil, moisture, food, and shelter). The ranges of animals can generally shift much faster than those of plants, and large migratory animals can move faster than small ones. In addition, migratory pathways must be available, such as northward flowing rivers as conduits for fish. Some migratory pathways may be blocked by development. All of these variations result in the break-up of existing ecosystems and formation of new ones, with unknown consequences[4].

Point to add: since climate change is happening so fast, mobile species may not able to move fast enough, and sedentary species (like trees) may not shift their ranges fast enough.

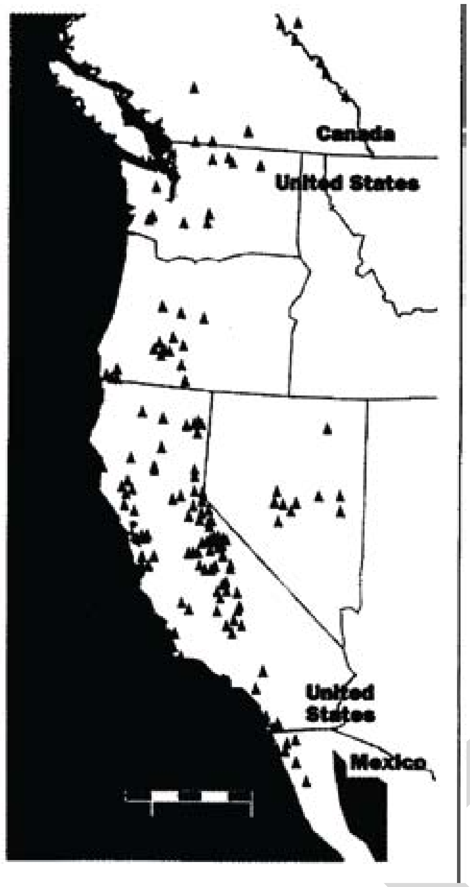


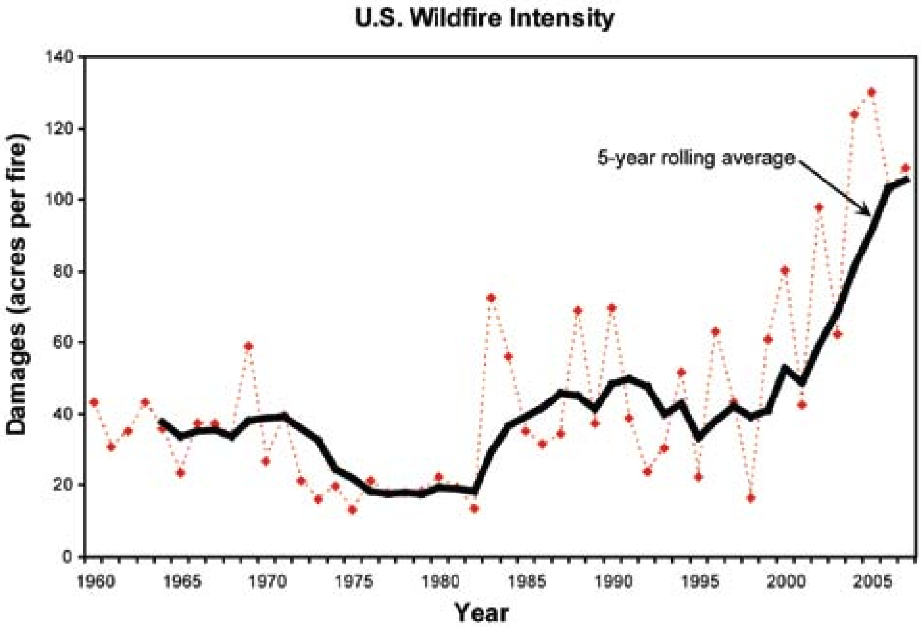
Figure source: Camille Parmesan

High resolution figure requested

There have been increases in fire, insect pests, disease pathogens, and invasive weed species, and more are projected.

Increases in frequency, intensity, and size of forest fires

In the western United States, especially in mid-elevation forests in the northern Rocky Mountains and Sierra Nevada, there have been significant increases in the frequency of large wildfires and in the length of the fire season. These changes are closely linked to earlier melting of snow in the spring, as well as increases in spring and summer temperatures. The earlier snowmelt extends the time during which ignitions can occur and contributes to drier conditions in mid-summer, leading to drier vegetation and potential fuel for fires. There is thus a clear linkage between changes in climate and the increase in fire frequency and severity.



Similar phenomena are occurring in northern forests across the continent, from Alaska through Canada. The area burned by wildfire has more than doubled between the decades of the 1960s and 1970s and the decades of the 1980s and 1990s. Both the size of fires and the number of fires due to lightning strikes appear to be correlated closely with the increase in burned area. Increased summer air temperatures are a key factor in this increase in fires in the northern forests, for much the same reasons as the changes in snowpack and temperatures in the mountain West.

Increase in insect pests

Insect pests are economically important stresses on forest ecosystems in the United States. Coupled with pathogens, they cost more than $1 billion annually in damages. Forest insect pests are well known to be sensitive to climatic variations in many stages of their life cycles. Changes in climate have contributed significantly to several major insect pest outbreaks in the United States and Canada over the past several decades. Mountain pine bark beetle in British Columbia attacking lodgepole pine is the largest of these: over 33 million acres of forest have been affected, by far the largest such outbreak in recorded history. Another 620,000 acres have been affected by pine bark beetle in Colorado. Spruce bark beetle has affected more than 2.5 million acres in Alaska and western Canada. The combination of drought and high temperatures has also led to serious insect infestations and death of pinyon pine in the Southwest, and to various insect pest attacks throughout the forests of the eastern United States.

In each case, there is an interaction of heat and drought, which tends to weaken trees' resistance to attack. There is also often a direct effect of higher temperatures on the insects themselves, such as warmer winters allowing survival of larvae through the coldest part of the year and generally higher temperatures accelerating the pests' life cycles and thus increasing their populations.

Disease pathogens and their carriers

Golden Toad, Costa Rica, now extinct

One consequence of a longer, warmer growing season and less extreme cold in winter is that opportunities are created for many insect pests and disease pathogens to flourish. Accumulating evidence links the spread of disease pathogens to a warming climate. For example, a recent study showed that widespread amphibian extinctions in the mountains of Costa Rica are linked to changes in climatic conditions[5].

A survey of recent scientific studies finds that diseases and the creatures that carry them have been expanding their geographic ranges as climate heats up. The findings confirm that, depending on their specific adaptations to current climate, many parasites, and the insects, spiders, and scorpions that carry and transmit diseases, die or fail to develop below threshold temperatures. Therefore, as temperatures rise, more of these disease-carrying creatures survive. For some species, rates of reproduction, population growth, and biting, can increase with increasing temperatures (up to a limit). Some parasites' development rates and infectivity periods also increase with temperature[6].

An analysis of diseases among marine species found that diseases were increasing for mammals, corals, turtles, and mollusks, while no trends were detected for sharks, rays, crabs, and shrimp[7].

Invasive plants

Problems involving invasive plant species arise from a mix of human-induced changes, including disturbance of the land surface (such as through grazing or development), deliberate or accidental transport of non-native species, the increase in available nitrogen, and rising carbon dioxide levels and the resulting climate change. Human-induced climate change is not generally the initiating factor, nor the most important one, but it is increasingly part of the mix.

Kudzu and other invasive weed species, along with native weeds and vines, disproportionately benefit from increased carbon dioxide compared to other native plants.

Increasing carbon dioxide levels stimulate the growth of most plant species, and some invasive plants are expected to respond with greater growth rates than non-invasive plants[4]. Beyond this, invasive plants appear to better tolerate a wider range of environmental conditions and may be more successful in a warming world because they can migrate and establish themselves in new sites more rapidly than native plants[8]. They are also not usually dependent on external pollinators or seed dispersers to reproduce. For all of these reasons, invasive plant species present a growing problem that is extremely difficult to control once unleashed.

Coastal and near-coastal ecosystems including wetlands and coral reefs are especially vulnerable to the impacts of climate change.

Coastal and near-shore marine ecosystems are vulnerable to a host of climate change related effects including increasing air and water temperatures, ocean acidification, changes in runoff from the land, sea-level rise, and altered currents. These changes have led to coral bleaching and diseases, shifts in species ranges, increased storm intensity in some regions, dramatic reductions in sea-ice extent and thickness along the Alaskan coast, and other significant changes to the nation's coastlines and marine ecosystems.

Coral Reefs

Coral reefs are very diverse ecosystems that support many other species by providing food and habitat. In addition to their ecological value, coral reefs provide billions of dollars in services including tourism, fish breeding habitat, and protection of coastlines. Human-induced carbon dioxide emissions and warming are causing changes that have enormous detrimental effects on coral reefs including rising water temperatures, ocean acidification, and increasing tropical storm intensity to some regions. In addition, corals face a host of other challenges related to human activities such as tourism, fishing, pollution, and development.

Corals are marine animals that host symbiotic algae that help nourish and give them their color. When corals are stressed by increases in water temperatures or ultraviolet light, they lose their algae and turn white, a process called coral bleaching. If the stress persists, the coral die. Intensities and frequencies of bleaching events clearly driven by warming in surface water have increased substantially over the past 30 years, leading to the death or severe damage of about a third of the world's corals[9].

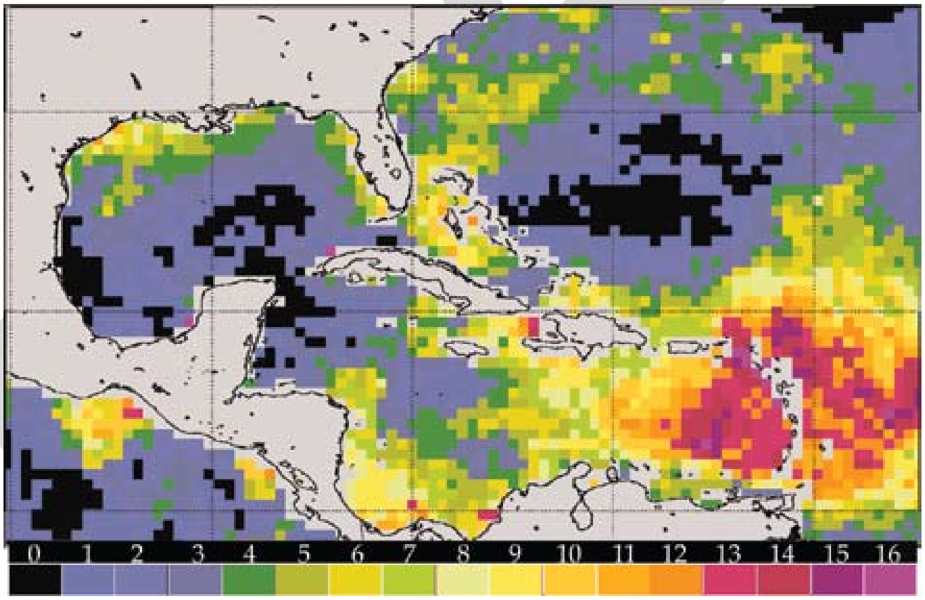
The United States has extensive coral reef ecosystems in the Caribbean, Atlantic, and Pacific Oceans. In 2005, the Caribbean basin experienced unprecedented water temperatures and resulting dramatic coral bleaching with some sites in the U.S. Virgin Islands seeing 90 percent of the coral bleached. Some corals began to recover when water temperatures decreased, but later that year disease appeared, striking the previously bleached and weakened coral. To date, 50 percent of the corals in Virgin Island National Park have died from the bleaching and disease events. In the Florida Keys, summer 2005 bleaching was also followed by disease in September[10].

Projections based on temperature increases alone suggest that within the next several decades, 60 percent of the world's corals are likely to be severely damaged or destroyed. But rising temperature is not the only stress coral reefs face. As carbon dioxide concentrations in the air increase, more carbon dioxide is absorbed into the world's oceans, leading to their acidification. This makes less calcium

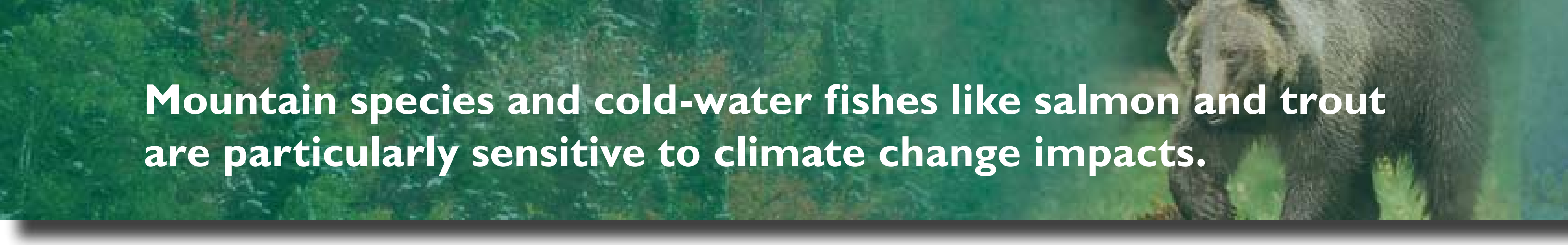
carbonate available for corals and other sea life to build their skeletons and shells. If carbon dioxide concentrations continue to rise and the resulting acidification proceeds, eventually, they will not be able to build these skeletons and shells at all. The combination of rising ocean temperatures, increasing ocean acidity, changes in light as sea level rises, increased storm intensity, and the other stresses could take coral reef ecosystems past a critical threshold for survival within decades. The loss of coral reefs would reverberate through the entire marine food web and ecosystem[10a].

Marine Fish

The distribution of marine fish and plankton are predominantly determined by climate so it is not surprising that marine species in U.S. waters are moving northward and that the timing of plankton blooms is shifting. Extensive shifts in the ranges and distributions of both warm- and cold-water species of fish have been documented in Europe and the North Atlantic, as well as in the oceans surrounding North America. In the Pacific, climate change is expected to cause an eastward shift in the location of tuna stocks[10b]. It is clear that such shifts are related to climate, including natural modes of climate variability such as El Niño-La Niña cycles. However, it is unclear how these modes of ocean variability will change as global climate continues to change, and therefore it is very difficult to predict quantitatively how marine fish and plankton species' distributions might change as a function of climate change[10a].



A measure of heat stress (NOAA's Coral Reef Watch Degree Heating Weeks) for 12 weeks before October 28, 2005 in the Caribbean Basin with the highest thermal stress ever recorded. Numbers greater than 4 indicate that some coral bleaching is expected, whereas numbers greater than 8 indicate that mass bleaching and mortality are expected.



Mountain species and cold-water fishes like salmon and trout are particularly sensitive to climate change impacts.

Mountain species

Animal and plant species that live in the mountains are among those particularly sensitive to rapid climate change. They include animal species such as the grizzly bear, bighorn sheep, pika, mountain goat, and wolverine. Major changes have already been observed in the pika as previously reported populations have disappeared entirely as climate has warmed over recent decades[11]. One reason mountain species are so vulnerable is that their suitable habitats are being compressed as climatic zones shift upward in elevation. Some species try to shift uphill with the changing climate but there may be other constraints related to food, other species present, and other variables. In addition, as species move up the mountains, those near the top simply run out of habitat.

A recent study found that fewer wild flowers are projected to grace the slopes of the Rocky Mountains as global warming causes earlier spring snowmelt. Larkspur, Aspen Fleabane, and Aspen Sunflower grow at an altitude of about 9500 feet where the winter snows are deep. Once the snow melts, the flowers form buds and prepare to bloom. But warmer springs mean that the snow has been melting earlier, leaving the buds exposed to frost (the percentage of buds that were frosted has doubled over the past decade). Frost doesn't kill the plants but does make them unable to seed and reproduce, meaning there will be no next generation. Insects and other animal species depend on the flowers for food, and other species depend on those species, so the loss is likely to propagate through the food chain[12].

Pika

Shifts in tree species on mountains in New England, where temperatures have risen 2 to 4ºF in the last 40 years, offer another example. Some mountain tree species have shifted uphill by 350 feet in the last 40 years – a rate much faster than expected. Tree communities were relatively unchanged at low and high elevations, but in the transition zone in between, at about 2600 feet elevation, the changes have been dramatic. Cold-loving tree species declined from 43 to 18 percent while warmer-loving trees increase from 57 to 82 percent. Overall, the transition zone shifted about 350 feet uphill in just a few decades, a surprisingly rapid rate since these are trees that live for hundreds of years. One possibility is that as trees were damaged or killed by air pollution, it left an opportunity for the warming-induced transition to occur more quickly. These results indicate that high-elevation forests may be jeopardized by climate change sooner than anticipated[13].

Illustration of species shifting upslope
under development

Cold-water fish

Salmon and other cold-water fish species in the United States are at particular risk from warming. Salmon are under threat from a variety of human activities, notably dams in the Northwest, but global warming is a growing source of stress. Dams often restrict salmon to lower and warmer elevations. Rising temperatures impact salmon in several important ways. As precipitation increasingly falls as rain rather than snow, it feeds floods that wash away salmon eggs incubating in the streambed. Warmer water leads eggs to hatch earlier in the year, so the young are smaller and more vulnerable to predators. Warmer conditions increase the fish's metabolism, taking energy away from growth and forcing the fish to find more food, but earlier hatching of eggs could put them out of sync with the insects they eat. Earlier melting of snow leaves rivers and streams warmer and shallower in summer and fall. Diseases and parasites tend to flourish in warmer water. Studies suggest that up to 40 percent of Northwest salmon populations may be lost by 2050[14].

Large declines in trout populations are also projected to occur around the United States. Over half of the wild trout populations will likely disappear from the southern Appalachian Mountains because of the effects of warming stream temperatures. Losses of western trout populations may exceed 60 percent in certain regions. About 90 percent of bull trout, which live in western rivers in some of the country's most wild places, may be lost due to warming. Pennsylvania is predicted to lose 50 percent of its trout habitat in the coming decades. Other states such as North Carolina and Virginia could lose up to 90 percent of their trout habitat due to warming[15].

Salmon returning up stream to spawn at Willow Creek, Oregon.

Arctic sea ice ecosystems are extremely vulnerable to warming.

Arctic wildlife

Perhaps most vulnerable of all to the impacts of warming are Arctic ecosystems that rely on sea ice, which is vanishing rapidly, and is projected to disappear entirely in summertime within this century. Algae that bloom on the underside of the sea ice form the base of a food web leading through zooplankton and fish to seals, whales, polar bears, and people. As the sea ice disappears, so too do these algae. The ice also provides a vital platform for ice-dependent seals (like the ringed seal) to give birth, nurse their pups, and rest. Polar bears use the ice as a platform from which to hunt their prey. The walrus rests on the ice near the continental shelf between its dives to eat clams and other shellfish. As the ice edge retreats away from the shelves to deeper areas, there will be no clams nearby[16].

Placeholder box for figure under development

[graphics: illustration of sea ice ecosystem]]

The Bering Sea off the west coast of Alaska produces our nation's largest commercial fish harvests as well as providing food for many Native Alaskans. Ultimately, the fish populations (and those of seabirds, seals, walruses, whales, etc.) depend on plankton blooms regulated by the extent and location of the ice edge in spring. As the sea ice continues to decline, the location, timing, and species make-up of the blooms is changing. The spring melt of sea ice in the Bering Sea has long provided material that feeds the clams, shrimp and other life forms on the ocean floor that in turn provide food for the walruses, gray whales, bearded seals, eider ducks, and many fish. The earlier ice melt resulting from warming, however, leads to later phytoplankton blooms that are largely consumed by zooplankton near the sea surface, vastly decreasing the amount of food reaching the living things on the ocean floor. This will radically change the make-up of the fish and other creatures, with significant repercussions for commercial and subsistence fishing[17].

Ringed seals give birth in snow caves on the sea ice, which protect the pups from extreme cold and predators. Warming leads to earlier snow melt which causes the snow caves to collapse before the pups are weaned. The small exposed pups may die of hypothermia or be vulnerable to predation by arctic foxes, polar bears, gulls, and ravens. Gulls and ravens are arriving in the Arctic earlier as springs become warmer, increasing their potential to prey on the seal pups.

Polar bears are the top predators of the sea ice ecosystem. Because they prey primarily on ice-associated seals, they are especially vulnerable to the disappearance of sea ice. The rapid rate of warming in Alaska and the rest of the Arctic in recent decades is sharply reducing the snow cover in which polar bears build dens and the sea ice they use as foraging habitat. Female polar bears build snow dens in which they hibernate for four to five months each year and in which they give birth to their cubs. Born weighing only about one pound, the tiny cubs depend on the snow den for warmth. The bear's ability to catch seals depends on the presence of sea ice. In that habitat, polar bears take advantage of the fact that seals must surface to breathe in limited opening in the ice cover. In the open ocean, bears lack a hunting platform, seals are not restricted in where they can surface, and successful hunting is very rare. On shore, polar bears feed little, if at all. Recent U.S. Geological Survey analysis suggests that two thirds of the world's polar bears will be gone by the middle of this century, and that Alaska's polar bears will be extinct within 75 years.

Continued warming will inevitably entail major changes in the sea ice ecosystem, to the point that its viability is in jeopardy. Some species will become extinct, while others may adapt to new habitats. The chances of species surviving the changes underway may depend critically on the rate of change. The current rates of change in the sea ice ecosystem are very steep relative to the life spans of animals like seals, walruses and polar bears, and as such, are a major threat to their survival[18].

Adaptation Strategies for Natural Environment and Biodiversity

Helping existing ecosystems adapt to climate change over the next few decades generally involves reducing other stresses on those systems and attempting to optimize their resilience. Beyond the next few decades, managers are likely to be faced with substantially changed conditions, requiring revised management goals and adaptation strategies. Although reducing existing stresses is a reasonable strategy for the present and other potential strategies can be identified for the future, they are largely untested and their effectiveness and costs are poorly understood. It will be critical for the institutions responsible for managing these ecosystems to collaborate on larger regional strategies than is currently the case.

Regional Climate Change Impacts

Climate change will pose unique sets of challenges and opportunities for each region of the country. Not only will the changes be different from one area to another, but even if they experienced similar climatic changes, the impacts would be different. Therefore, the following pages will describe the key climate change impacts in each region of the country.

Island maps are still under development

Northeast

The Northeast has significant geographic and climatic diversity within its relatively small area. The character and economy of the Northeast have been shaped by many aspects of its climate including its snowy winters, colorful autumns, and variety of extreme events such as nor'easters, ice storms, and heat waves. This familiar climate has already begun changing in noticeable ways. Since 1970, the annual average temperature in the Northeast has increased by 2°F, with winter temperatures rising twice this much[1]. This warming has resulted in many other climate-related changes, including:

- More frequent days with temperatures above 90°F
- A longer growing season
- Less winter precipitation falling as snow and more as rain
- Reduced snowpack and increased snow density
- Earlier breakup of winter ice on lakes and rivers
- Earlier spring snowmelt resulting in earlier peak river flows
- Rising sea-surface temperatures and sea levels

All of these observed regional changes are consistent with ones expected to result from global warming. The Northeast is projected to face continued warming and more extensive climate-related changes, some of which could dramatically alter the region's economy, landscape, character, and quality of life.

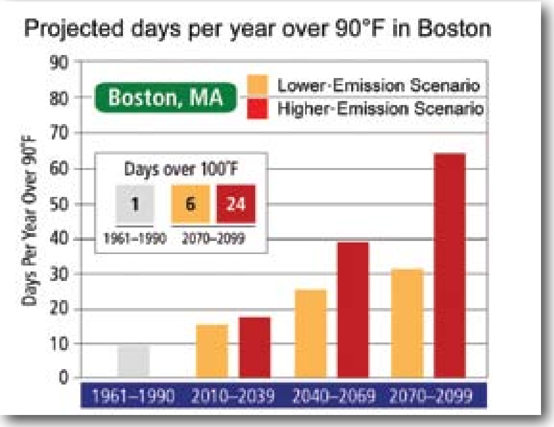
Over the next several decades, temperatures are projected to rise an additional 2.5 to 4°F in winter and 1.5 to 3.5°F in summer. By mid-century and beyond, however, today's emissions choices generate starkly different climate futures, with a lower emissions scenario resulting in much smaller climatic changes and resulting impacts[2,3]. By late this century, under a higher-emissions scenario:

- Winters in the Northeast are projected to warm by 8 to 12°F and summers by 6 to 14°F.
- The length of the winter snow season would be cut in half across northern New York, Vermont, New Hampshire, and Maine, and reduced to a week or two in southern parts of the region.
- Cities that today experience few days above 100°F each summer would average 20 such days per summer, while certain cities, such as Hartford and Philadelphia, would average nearly 30 days over 100°F.
- Short-term (one- to three-month) droughts are projected to occur as frequently as once each summer in the Catskill and Adirondack Mountains, and across the New England states.
- Hot summer conditions would arrive three weeks earlier and last three weeks longer into the fall.
- Global average sea level is conservatively projected to rise one to two feet, with the potential for much larger rises.

Extreme heat and declining air quality are projected to pose increasing problems for human health, especially in urban areas.

Heat waves, which are currently rare in the region, are projected to become much more commonplace in a warmer future, with major implications for human health (see *Human Health* sector). Future impacts in the Northeast are evident in the projections of the number of summer days with temperatures over 90°F and over 100°F, illustrated for the city of Boston[4].

In addition to the physiological stresses associated with hotter days and nights[5], for cities that now experience ozone pollution problems, the number of days that fail to meet federal air-quality standards is projected to increase with rising temperatures[6] (see *Human Health* sector).



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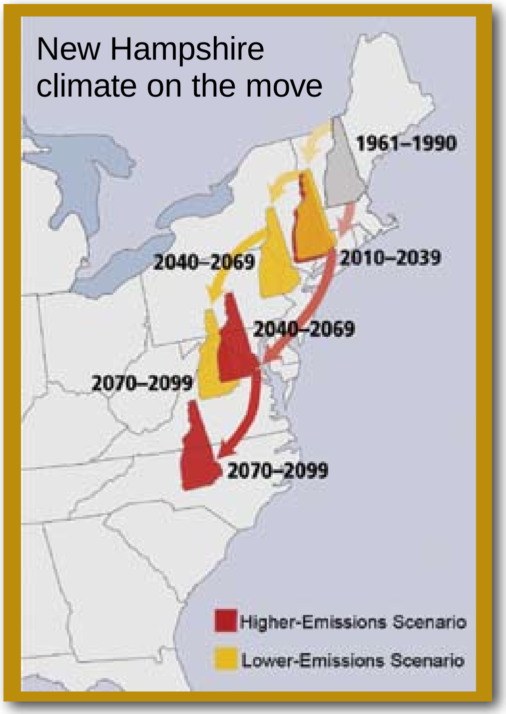

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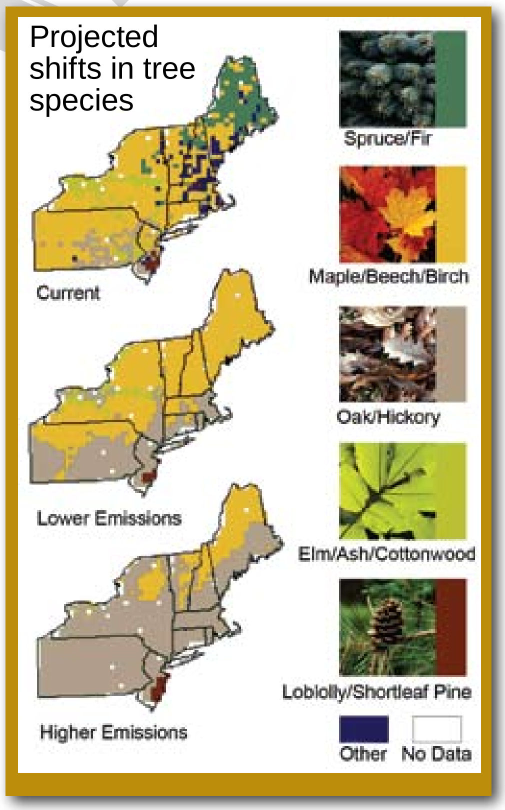
Projected changes in the summer heat index provide a graphic sense of how different the climate of the Northeast is projected to be under low *versus* high emissions scenarios. Yellow arrows track what summers are projected to feel like under a lower emissions scenario, while red arrows track projections for a higher emissions scenario. For example, under the higher emission scenario, by late in this century residents of New Hampshire would experience summer climate more like what occurs today in North Carolina. The effects of this kind of change will be particularly problematic in this region, since air conditioning is considerably less prevalent in New England homes, with some form of air conditioning being present in only about 58 percent of homes in this region, compared to the national average of 77 percent[7].

Agricultural production, including dairy, fruit, and maple syrup, will be increasingly affected as favorable climates shift.

Large portions of the Northeast are likely to become unsuitable for growing popular varieties of apples, blueberries, and cranberries under a higher-emissions scenario[8,9]. Climate conditions suitable for maple/beech/birch forests are projected to shift dramatically northward, eventually leaving only a small portion of the Northeast with a maple sugar business[10].

The dairy industry is the most important agricultural sector in this region, with annual production worth $3.6 billion[11]. Heat stress in dairy cows depresses both milk production and birth rates for periods of weeks to months[12]. By late this century, all but the northern parts of Maine, New Hampshire, New York, and Vermont are projected to suffer declines in July milk production under the higher-emissions scenario. In parts of Connecticut, Massachusetts, New Jersey, New York, and Pennsylvania, a ten to 20 percent or greater decline in milk production is projected. Under the lower-emissions scenario, however, reductions in milk production of up to ten percent remain confined primarily to New Jersey and small areas of Pennsylvania[13]. This analysis used average monthly temperature and humidity data that do not capture daily variations in heat stress and projected increases in extreme heat. Nor did the analysis directly consider farmer responses, such as installation of potentially costly cooling systems. On balance, these projections are likely to underestimate impacts on the dairy industry.



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Severe floods due to sea-level rise and heavy downpours are projected to occur more frequently.

Many current sea-level projections do not fully account for changes in ice flow dynamics such as those recently observed on the world's major ice sheets, and thus are likely to be underestimated[14]. However, even under these projections, the densely populated coasts of the Northeast face substantial increases in the extent and frequency of coastal flooding, erosion, property damage, and loss of wetlands. New York State alone has more than $1.9 trillion in insured coastal property[15]. Much of this coastline is exceptionally vulnerable to sea-level rise and related impacts. Some major insurers have withdrawn coverage from thousands of homeowners in coastal areas of the Northeast, including New York City.

Increased flood risk in New York City

The light blue area in these maps depicts today's FEMA 100-year flood zone for New York City (*i.e.*, the area of the city that is expected to be flooded once every 100 years). With additional sea-level rise by 2100 under the higher-emissions scenario, this area is projected to have a ten percent chance of flooding in any given year; under the lower-emissions scenario, a five percent chance. Critical transportation infrastructure located in the Battery area could be flooded far more frequently unless protected. The 100-year flood at the end of the century (not mapped here) is projected to inundate a far larger area of New York City, especially under the higher-emissions scenario[26].

Rising sea levels are projected to increase the frequency and severity of damaging storm surges and flooding. Under a higher-emissions scenario, what is now considered a once-in-a-century coastal flood in New York City is projected to occur at least twice as often by mid-century, and ten times as often, or once per decade on average, by late-century. With lower emissions, today's 100-year flood is projected to occur once every 22 years on average by late century[16].

The projected reduction in snow cover will affect winter recreation and the industries that rely upon it.

Winter snow and ice sports, which are worth some $7.6 billion annually to the regional economy, will be particularly affected by warming[17]. Of this total, alpine skiing and other snow sports (not including snowmobiling) account for $4.6 billion annually. Snowmobiling, which now rivals skiing as the largest winter recreation industry in the nation, accounts for the remaining $3 billion[18]. Other winter traditions, ranging from skating and ice fishing on frozen ponds and lakes, to cross-country (Nordic) skiing, snowshoeing, and dogsledding, are integral to the character of the Northeast, and for many residents and visitors, its desirable quality of life.

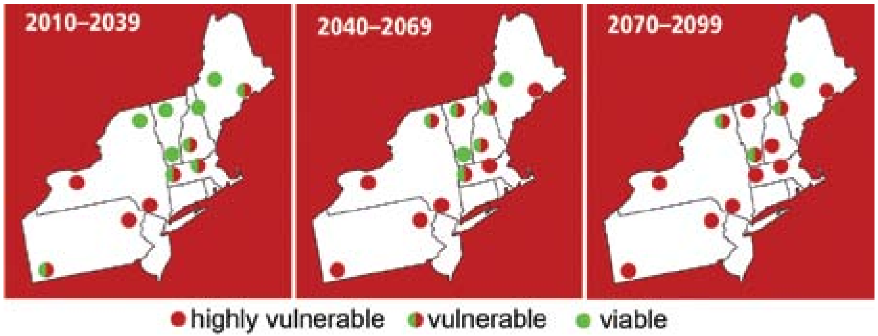
Warmer winters will shorten the average ski and snowboard seasons, increase artificial snowmaking requirements, and drive up operating costs. While snowmaking can enhance the prospects for ski resort success, it requires a great deal of water and energy, as well as very cold nights, which are becoming less frequent. Analyses of projected changes in ski-season length, the probability of being open during the Christmas to New Year holiday, and snowmaking

Adaptation: Raising a Sewage Treatment Plant in Boston

Boston's Deer Island sewage treatment plant was designed and built taking future sea-level rise into consideration. Because the level of the plant relative to the level of the water at the outfall is critical to the amount of rainwater and sewage that can be treated, the plant was built 1.9 feet higher than it would otherwise have been to accommodate the amount of sea-level rise projected to occur by 2050, the planned life of the facility.

The planners recognized that the future would be different than the past and they decided to plan for the future based on the best available information. They assessed what could be easily and inexpensively changed at a later date *versus* those things that would be more difficult and expensive to change later. For example, increasing the plant's height would be less costly to incorporate in the original design, while armoring the island could be added at a later date as needed at a relatively small cost.

Ski areas at risk under higher emissions scenario

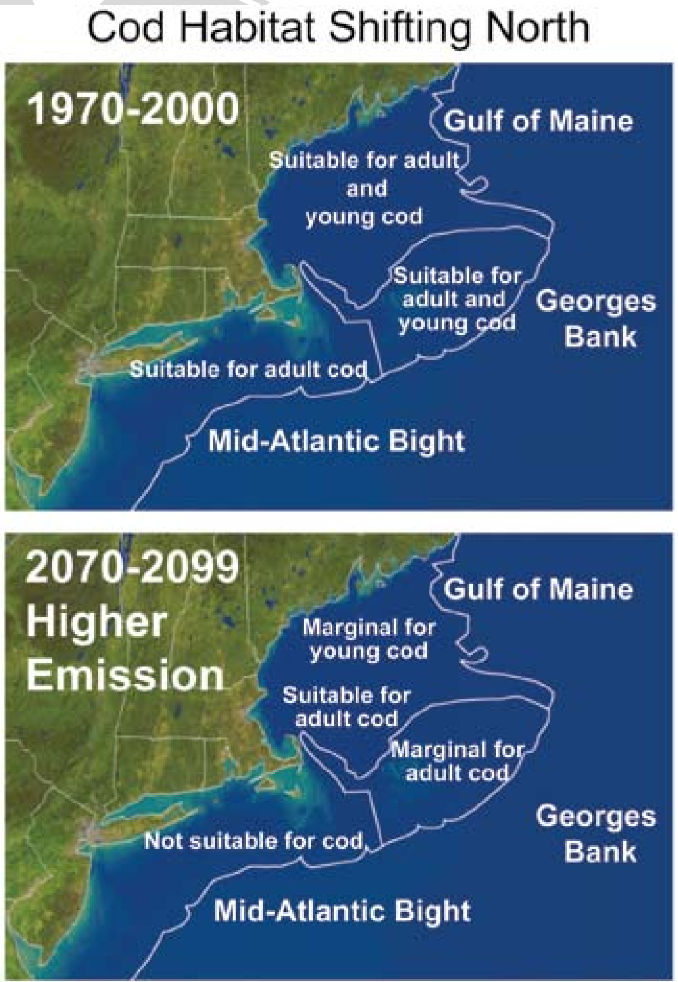


(see endnote 26)

requirements suggest that most ski areas in the Northeast will have a projected average season of less than 100 days and a less-than-75-percent probability of operating during the lucrative holiday period, making them highly vulnerable to climate change. Only one area in the region is projected to support viable ski resorts by the end of this century under a higher-emissions scenario[19]. Without the opportunity to benefit from snowmaking, the prospects for the snowmobiling industry are even worse. Most of the region is likely to have a marginal or non-existent snowmobile season by mid-century.

The center of lobster fisheries is projected to continue its northward shift and the cod fishery on Georges Bank is likely to be diminished.

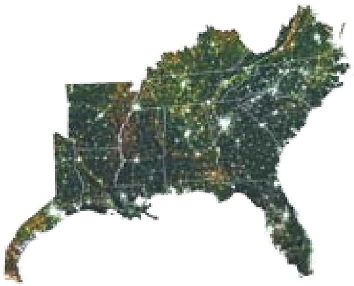
Lobster catch has increased dramatically in the Northeast as a whole over the past three decades, though not uniformly[20,21]. Catches in the southern part of the region peaked in the mid-1990s, and have since declined sharply, beginning with a 1997 die-off in Rhode Island and Buzzards Bay (Massachusetts) associated with the onset of a temperature-sensitive bacterial shell disease, and accelerated by a 1999 lobster die-off in Long Island Sound. The commercial potential of lobster harvest appears limited in its southern extent, today, by this temperature-sensitive shell disease and in the coming decades, by rising nearshore water temperatures. Analyses also suggest that warming conditions in the northern regions of the Gulf of Maine, longer growing season, more rapid growth, an earlier hatching season, more nursery grounds suitable for larval settlement, and faster planktonic development could increase lobster survival and settlement in these northern waters[22].



(adapted from data, see endnote 26)

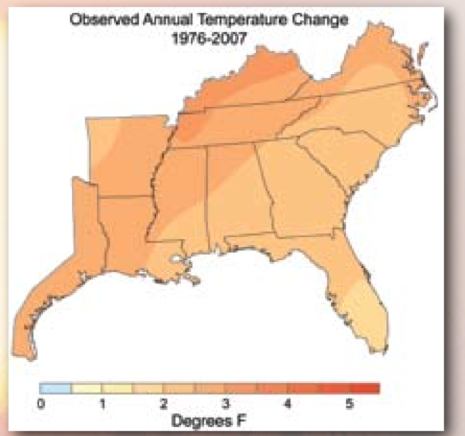
Cod populations throughout the North Atlantic are adapted to a wide range of seasonal ocean temperatures, including average annual temperatures the sea floor ranging from 36 to 54°F. A maximum ocean temperature of 54°F represents the threshold of thermally suitable habitat for cod and the practical limit of cod distribution[23]. Temperature also influences both the location and timing of spawning, which in turn affects the subsequent growth and survival of young cod. Studies indicate that increases in average annual bottom temperatures above 47°F will lead to a decline in growth, survival, and recruitment[24,25].

In ocean waters off the Northeast coast, cod are currently at the southern edge of their thermal habitat, and young cod are uncommon south and west of Georges Bank. Under a higher emissions scenario, Georges Bank, which has historically been one of the most important centers of cod production, is projected to become unsuitable habitat for young cod[26].

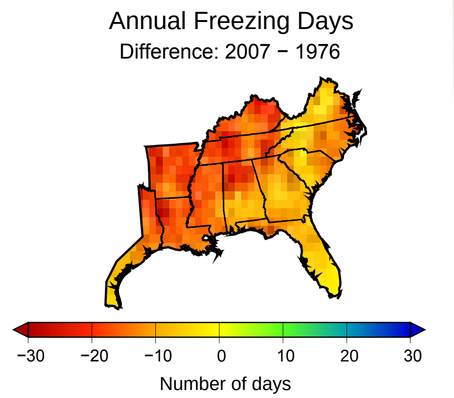


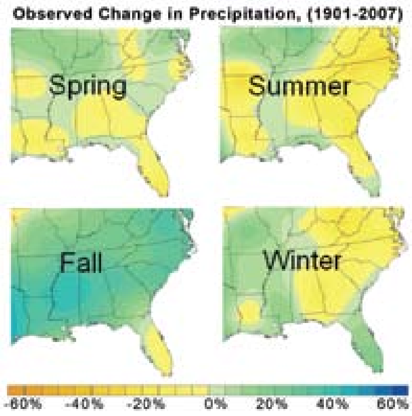
Southeast

The climate of the Southeast is uniquely warm and wet, with mild winters and high humidity, compared with the rest of the continental U.S. The annual average temperature in the Southeast rose about 2°F between 1970 and 2007, with the greatest increase occurring during the winter months. The number of freezing days declined by 4 to 7 days for most of the region since the mid-1970's. Average fall precipitation increased by 30 percent for the southeastern region since 1901. The decline in fall precipitation in South Florida contrasts strongly with the regional average. There has been an increase in heavy downpours in many parts of the region[1,2] while the percentage of the region experiencing moderate to severe drought increased over the past three decades. The area of moderate to severe spring and summer drought increased by 12 percent and 14 percent, respectively, since the mid-1970s. Even in the fall months, when precipitation tended to increase in most of the region, the extent of drought increased by 9 percent.

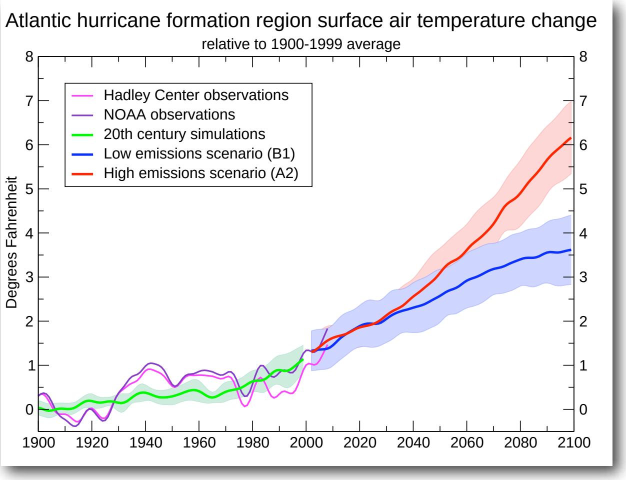


Climate models project continued warming in all seasons across the Southeast and an increase in the rate of warming through the end of this century. The projected rates of warming are more than double those experienced in the Southeast since 1975, with the greatest temperature increases projected to occur in the summer months. The number of very hot days is projected to rise at a greater rate than the average temperature. Under a lower emissions scenario, average temperatures in the region are projected to rise by about 4.5°F by the 2080s, while a higher emissions scenario yields about 9°F of average warming (with about a 10.5°F increase in summer, and a much higher heat index). Rainfall is projected to decline in South Florida during this century. Climate models provide divergent results for future precipitation for the remainder of the Southeast, though they suggest that the upper tier of states in the region will tend to receive more annual rainfall than the Gulf Coast. Because higher temperatures lead to more evaporation of moisture from soils and water loss from plants, moisture deficits and droughts are likely to continue to increase.





An increase in the intensity of hurricanes is likely to accompany global warming as a function of higher sea surface temperatures, which have been observed globally, including in the Atlantic hurricane formation region. A measure of hurricane power based on intensity, duration, and frequency has risen over recent decades in the North Atlantic, correlated with rising sea surface temperature[3,4,5,6,7]. An increase in average summer wave heights along the U.S. Atlantic coastline since 1975 has also been attributed to a progressive increase in hurricane power[8]. Future temperature projections for the ocean region where Atlantic hurricanes form suggest that the warming observed during the past century may double by 2030[8a]

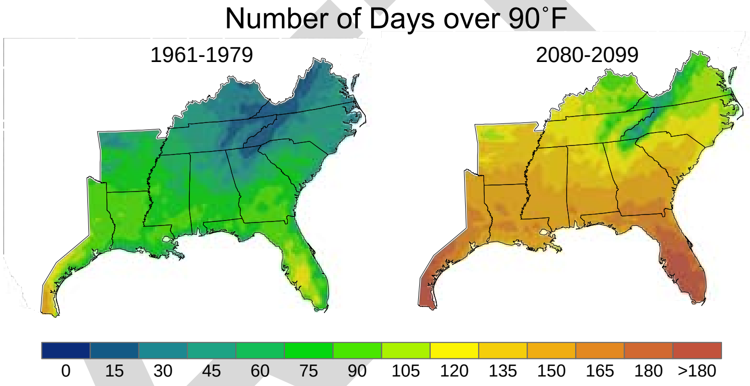


Projected increases in air and water temperatures will cause heat-related stresses.

The warming projected for the Southeast during the next 50 to 100 years will create heat-related stress for people, agricultural crops, livestock, trees, transportation and other infrastructure, fish, and wildlife. The average temperature change is not as important for all of these sectors and natural systems as the projected increase in maximum and minimum temperatures. Examples of potential impacts include:

- Widespread illness and loss of life due to increased summer heat stress[9].
- Decline in forest growth and agricultural crop production due to the combined effects of thermal stress and declining soil moisture[10].
- Buckling of pavement and railways[11,12].
- Decline in dissolved oxygen in stream, lakes, and shallow aquatic habitats leading to fish kills and loss of aquatic species diversity.
- Decline in production of cattle, poultry, and other livestock[12a]. Significant impacts on beef cattle occur at continuous temperatures in the 90-100°F range, increasing in danger as the humidity level increases (see *Agriculture* sector)[13].

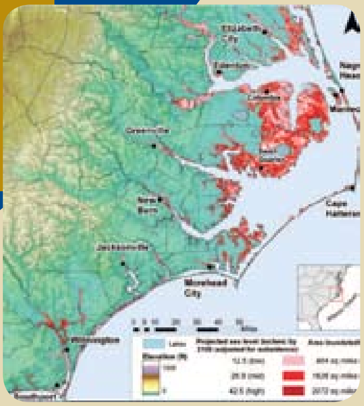
A reduction in the number of days below freezing is likely to reduce the loss of human life due to cold-related stress, but the number of cold-related deaths is generally much lower than the percentage due to heat stress[14,15]. Effects of the projected increases in temperature include more frequent outbreaks of shellfish-borne diseases in coastal waters, altered distribution of native plants and animals, elimination of many threatened and endangered species, displacement of native species by invasive species, and more frequent and intense wildfires.


Number of Days over 90˚F

Decreased water availability will impact the economy as well as natural systems.

Decreased water availability due to increased temperature (which increases moisture lost to evaporation and plant water loss to the atmosphere), and increased societal demand will very likely affect many sectors of the southeastern economy. The hydrology of natural systems is also affected by both climate change, and human response strategies such as an increase in storage capacity (dams) and an increase in acreage of irrigated cropland[16]. The 2007 water shortage in the Atlanta region created serious conflicts between three states, the U.S. Army Corps of Engineers (which operates the dam at Lake Lanier), and the U.S. Fish and Wildlife Service, which is charged with protecting endangered species. Streamflow and biological diversity can be reduced or eliminated as humans seek to adapt to climate change by manipulating water resources[17]. During droughts, recharge of groundwater will decline as the temperature and spacing between rainfall events increases as projected. An increase in groundwater pumping will deplete aquifers and place increasing strains on surface water resources. Increasing evaporation and plant water loss rates alter the balance of runoff and groundwater recharge and is likely to result in saltwater intrusion into shallow aquifers in many parts of the Southeast[17].

Placeholder for Sea-level rise map



(see endnote 26)

Accelerated sea-level rise and increased tropical storm intensity will have serious impacts.

The accelerating rate of sea-level rise and the likelihood of increased hurricane intensity are among the most costly consequences of climate change, due in large part to the concentration of development in the coastal zone. As sea level rises, coastal shorelines will retreat, and low-lying areas will be inundated more frequently, if not permanently, by the advancing sea. As temperature increases and rainfall patterns change, soil moisture and runoff to the coast are likely to be altered. The salinity of estuaries, coastal wetlands, and tidal rivers will likely increase in the southeastern coastal zone, thereby restructuring coastal ecosystems and displacing them further inland. More frequent storm surge flooding and permanent inundation of coastal ecosystems and communities is likely in some low-lying areas, particularly along the Central Gulf coast where the land surface is sinking[18, 20]. A rapid acceleration in the rate of increase in sea-level rise could potentially threaten a large portion of the Southeastern coastal zone. The likelihood of a catastrophic increase in the rate of sea-level rise is dependent upon ice sheet response to warming, which is the subject of much scientific uncertainty[19].

An increase in hurricane intensity would adversely affect low-lying coastal ecosystems and coastal communities along the Gulf and South Atlantic coastal margin. An increase in intensity has implications for runoff, river flooding, and coastal erosion. Strong hurricanes also pose a severe risk to people and personal property, public infrastructure, and coastal ecosystems in the Southeast, and this risk will likely be exacerbated[18, 20]. Hurricanes have their greatest impact at the coastal margin where they make landfall, causing storm surge, severe beach erosion, inland flooding, and wind-related casualties for both cultural and natural resources. Recent examples of our vulnerability to severe hurricanes include Katrina and Rita in 2005, which were responsible for the loss of more than 1800 lives and the net loss of 217 square miles of low-lying coastal marshes and barrier islands in South Louisiana[10,21].

Fish processing plant

Ecological thresholds are likely to be crossed, causing the rapid restructuring of ecosystems and the services they provide.

Ecological systems provide numerous important services that have high economic and cultural value in the Southeastern region. Ecological effects cascade among both living and physical systems, as illustrated in the following examples of ecological disturbances that result in "non-linear" responses, as opposed to a gradual and proportional response to warming:

- the sudden (as in a major hurricane) loss of coastal landforms that serve as a storm surge barrier for natural resources and communities[10, 22].
- an increase in sea level with no apparent effect until an elevation is reached that allows widespread, rapid salt water intrusion into coastal forests and fresh water aquifers[23].
- lower soil moisture, higher temperature, and higher fuel loads due to CO_2 enrichment, that lead to intense wildfires or pest outbreaks (such as the southern pine beetle) in southeastern forests[24], intense droughts that lead to the drying of lakes, ponds, and wetlands, and the local or global extinction of riparian and aquatic species[17].
- a initial increase followed by a precipitous decline of wetland-dependent coastal fish and shellfish populations due to the rapid loss of coastal marsh[25].

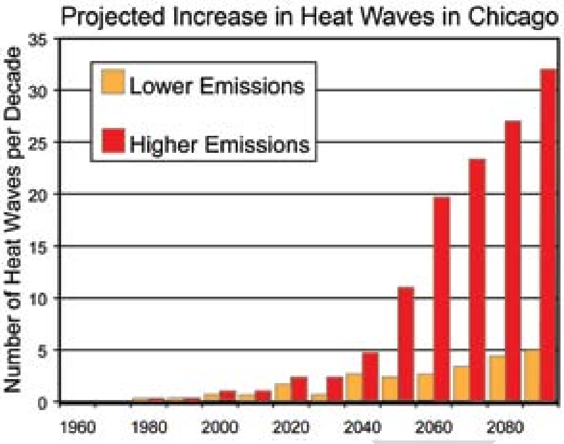
Quality of life will be affected by increasing heat stress, water scarcity, and severe weather events, and reduced availability of insurance for at-risk properties.

Over the past century, the southeastern "sunbelt" has attracted people, industry, and investment. The population of Florida more than doubled in size during the past three decades, and growth rates in most other southeastern states were in the range of 45 to 75 percent concentrated in coastal counties. Future population growth and the quality of life for existing residents is likely to be affected by the many challenges associated with climate change, such as reduced insurance availability, and increases in water scarcity, sea-level rise, extreme weather events, and heat stress.

Midwest

Model projections of Midwest climate indicate that by late this century, summers in Illinois are expected to feel like current summers in Texas under business-as-usual emissions and the resulting climate change[1].

While there is year-to-year variability, average temperatures in the Midwest have increased in recent decades, with the largest increases in winter. The length of the frost-free season has increased by over a week, mainly due to earlier dates for the last spring frost, which has lengthened the growing season. Heavy downpours are now twice as frequent as they were a century ago. Both summer and winter precipitation has been above average for the last three decades, the wettest period in a century. The Midwest has experienced two record-breaking floods in the past 15 years. There has been a decrease in lake ice, including on the Great Lakes. Heat waves have also been more frequent in the past few decades[1,2,3].



(see endnote 2)

Public health and quality of life, especially in cities, will be negatively affected by increasing heat waves, reduced air quality, and insect- and water-borne diseases.

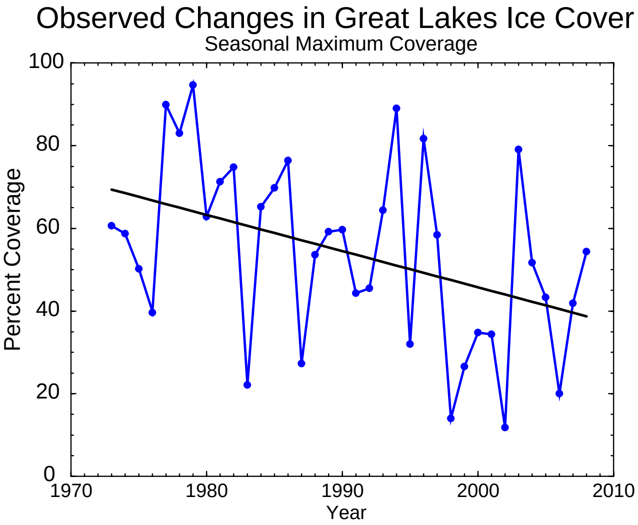
Heat waves that are more frequent, more severe, and longer-lasting are projected. The increased frequency of hot days and the longer length of the heat wave season will be more than twice as great under the higher emissions scenario than the lower[4]. Events such as the Chicago heat wave of 1995 (700-plus deaths) will become more common. Under the lower emissions scenario, such a heat wave is projected to occur every other year in Chicago, while under the higher emissions scenario, there would be about three such heat waves per year. Even more severe heat waves, such as the one that claimed tens of thousands of lives in Europe in 2003, are projected to become more frequent in a warmer world, occurring every other year in the Midwest by the end of the century under the higher emissions scenario[5].

During heat waves, high electricity demand combines with climate-related limitations on energy production capabilities (see *Energy Production and Use* sector), increasing the likelihood of electricity shortages and resulting in brown-outs or even black-outs, leaving people without air conditioning and ventilation when they need it most. This occurred during the 1995 Chicago/Milwaukee heat wave. In general, electricity demand for air conditioning is projected to significantly increase in summer, while oil and gas demand for heating will decline in winter.

One characteristic of human-induced warming is that nighttime temperatures are rising even faster than daytime temperatures. In addition, cities tend to retain more heat at night than the surrounding countryside because their concrete and asphalt hold heat, a phenomenon known as the “urban heat island effect.” Heat waves take a greater toll in illness and death when there is little relief from heat at night, and that is what is being currently observed and projected for the future.

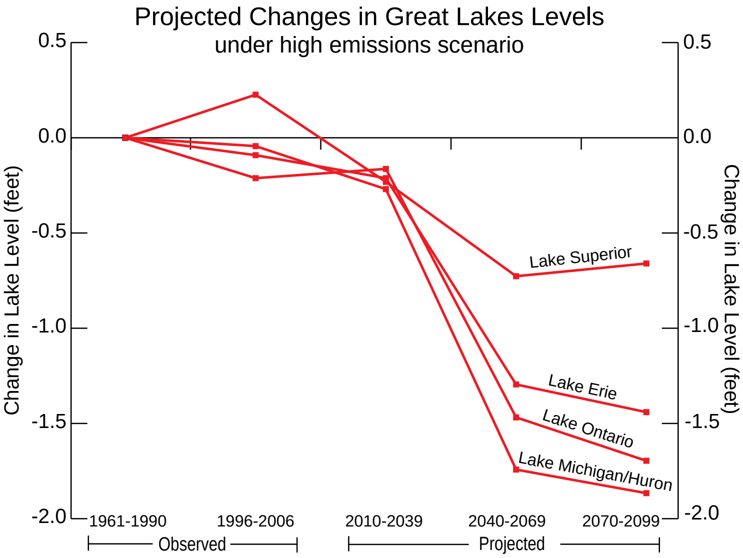
Declining air quality is a related concern. Higher summer air temperatures mean more ground-level ozone or urban smog, which causes respiratory problems for many people, especially those who are young, old, or have asthma or allergies. Unless the emissions of pollutants that lead to ozone formation are reduced significantly, there will be more ground-level ozone as a result of higher air temperatures[6].

Insects such as ticks and mosquitoes that carry diseases will survive winters more easily and produce larger populations in a warmer Midwest[7]. An increasing risk of diseases such as West Nile virus is thus a growing concern. Water-borne diseases are another public health issue as many pathogens thrive in warmer conditions.



Under higher emissions scenarios, significant reductions in Great Lakes water levels will impact shipping, infrastructure, beaches, and ecosystems.

The Great Lakes are a natural resource of tremendous significance, containing 20 percent of the planet's fresh surface water, and serving as the focus of the industrial heartland of the nation. Higher temperatures will mean more evaporation and hence a likely reduction in the Great Lakes' water levels. Reduced lake ice increases evaporation in winter, contributing to the decline. Under a lower emissions scenario, water levels in the Great Lakes are projected to fall no more than one foot, but under a higher emissions scenario, they are projected to fall between one and two feet. The greater the temperature rise, the higher the chance of a major decrease in lake levels. Even a decrease of one foot, combined with normal fluctuations, can result in significant lengthening of the distance to the lakeshore in many places. There are also potential impacts on beaches, coastal ecosystems, dredging requirements, infrastructure, and shipping. For example, lower lake levels reduce "draft," or the distance between the water line and the bottom of the ship, which lessens the ship's ability to carry freight. Ocean-going vessels, sized for passage through the St. Lawrence Seaway, lose about 100 tons of capacity for each inch of draft lost[7]. These impacts will have costs, including increased shipping, repairs and maintenance costs, and lost recreation and tourism dollars.



Average Great Lakes levels depend on the balance between precipitation (and corresponding runoff) in the Great Lakes Basin on one hand and evaporation and outflow on the other. Evaporation depends on the extent of ice cover in winter. As a result, lower emissions scenarios with less warming show less reduction in lake levels than higher emissions scenarios.

Increasing precipitation in winter and spring, more heavy downpours, and greater evaporation in summer will mean more periods of both floods and water deficits.

Precipitation is projected to increase in winter and spring, and to become more intense throughout the year. This pattern is expected to lead to more frequent flooding and resulting infrastructure damage. Heavy downpours also tend to overload drainage systems and water treatment facilities, increasing the risk of water-borne diseases. Such an incident occurred in Milwaukee in 1993 when the water supply was contaminated with the parasite *Cryptosporidium*, causing 403,000 reported cases of gastrointestinal illness and 54 deaths.

In Chicago, rainfall of more than 2.5 inches per day is an approximate threshold beyond which combined water and sewer systems overflow into Lake Michigan. This generally results in beach closings to reduce the risk of disease transmission. Rainfall above this threshold is projected to occur twice as often during this century under the lower emissions scenario and three times as often under the higher emissions scenario[8]. Similar increases are expected across the Midwest.

More intense rainfall can lead to floods that cause significant impacts regionally and even nationally. For example, the Great Flood of 1993 caused catastrophic flooding along 500 miles of the Mississippi and Missouri River systems, affecting one-quarter of all U.S. freight (see *Transportation* sector)[9]. Another example was a record-breaking 24-hour rainstorm in July 1996, which resulted in flash flooding in Chicago and its suburbs, causing extensive damage and disruptions, with some commuters not being able to reach Chicago for three days (see *Transportation* sector).[10] Another record-breaking storm took place in August 2007. Increases in such events are likely to cause greater property damage, higher insurance rates, a heavier burden on emergency management, increased clean-up and rebuilding costs, and a growing financial toll on businesses, homeowners, and insurers.

In the summer, with increasing evaporation rates and longer periods between rainfalls, the likelihood of droughts will increase and water levels in rivers, streams, and wetlands is likely to decline. Lower water levels could also create problems for river traffic, reminiscent of the stranding of more than 4000 barges on the Mississippi River during the drought in 1988. Reduced summer water levels are also likely to reduce the recharge of groundwater, cause small streams to dry up, and reduce the area of wetlands in the Midwest.

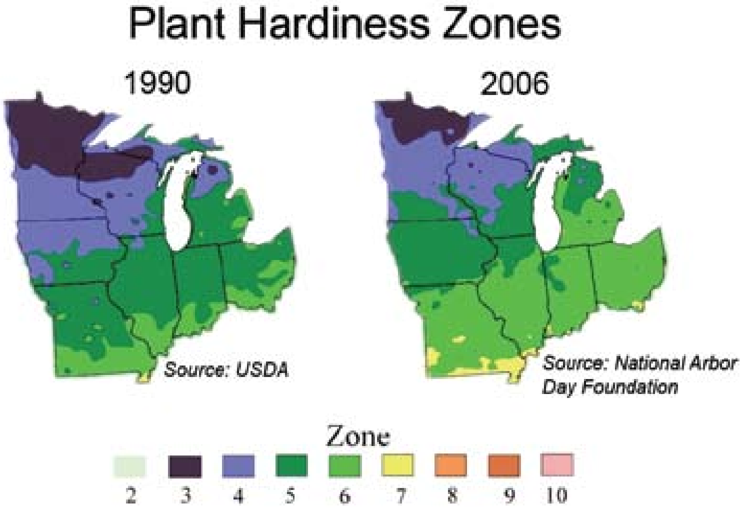
While a longer growing season provides the potential for increased crop yields, increases in heat waves, floods, droughts, insects, and weeds will present increasing challenges to crops, livestock, and forests.

The projected increase in winter and spring precipitation and flooding would delay planting and crop establishment. Longer growing seasons and increased carbon dioxide have positive effects on some crop yields, but this is counter-balanced by additional disease-causing pathogens, insect pests, and weeds (including invasive weeds) which have negative effects on yields. Livestock production is expected to become more costly as higher temperatures stress livestock, decreasing productivity and increasing costs associated with the needed ventilation and cooling equipment.

Plant hardiness zones in the Midwest are likely to shift one-half to one full zone about every 30 years. By the end of the century, plants now associated with the Southeast will be found throughout the Midwest. Impacts on forests are likely to be mixed as higher carbon dioxide and nitrogen levels act as fertilizers, increasing growth, but decreasing air quality. In addition, more frequent droughts and hence, fire hazards, and more destructive insect pests such as gypsy moths, hinder plant growth. Insects, historically controlled by cold winters, more easily survive milder winters and produce larger populations in a warmer climate (see *Agriculture* sector).

Native species will face increasing threats from rapidly changing climate conditions, pests, diseases, and invasive species moving in from warmer regions.

As air temperatures increase, so will water temperatures. This will lead to earlier and longer vertical separation of the layers of the lake water in summer, which will effectively cut off oxygen from bottom layers, increasing the risk of oxygen-poor or oxygen-free "dead-zones" that kill fish and other living things. Warmer water and low-oxygen conditions in the bottom layer of lakes also mobilizes mercury and other contaminants in lake sediments. These increasing quantities of contaminants will be taken up in the aquatic food chain, adding to the existing health hazards to all species that eat fish from the lakes, including people.


Plant Hardiness Zones

1990

2006

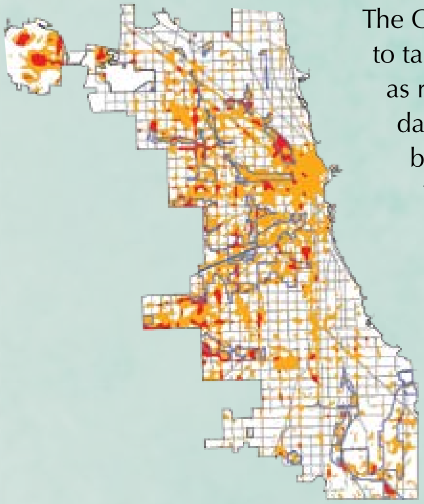
Source: USDA

Source: National Arbor Day Foundation

Populations of cold-water fish, such as brook trout, lake trout, and whitefish, are expected to decline dramatically, while populations of cool-water fish such as muskie, and warm-water species such as small-mouth bass and bluegill, will take their place. Aquatic ecosystem disruptions will likely be compounded by invasions by non-native species, which tend to thrive under a wide range of environmental conditions. Native species, adapted to a narrower range of conditions, are expected to decline.

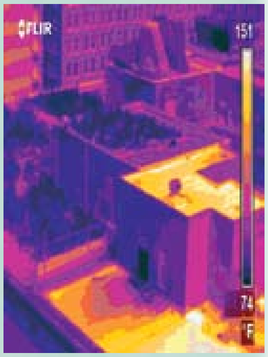
All major groups of animals, including birds, mammals, amphibians, reptiles, and insects, will be changed by local extinctions and other species moving into the Midwest region. The potential for animals to shift their ranges to keep pace with the changing climate will be inhibited by major urban areas and the presence of the Great Lakes.

Adaptation: Chicago Tries to Cool the Urban Heat Island

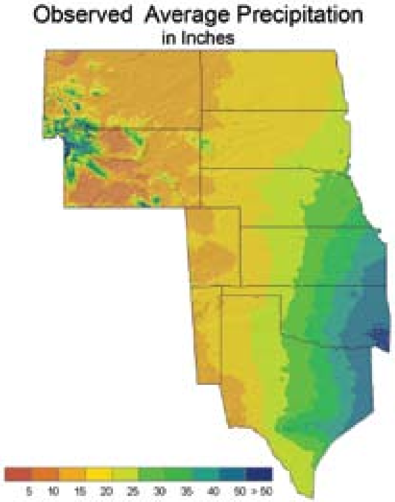


The City of Chicago produced a map of urban hot spots to use as a planning tool to target areas that could most benefit from heat island reduction initiatives such as reflective or green roofing and tree planting. Created using satellite images of daytime and nighttime temperatures, the map shows the hottest 10 percent of both day and night temperatures in red, and the hottest 10 percent of either day or night in orange.

The City is working to reduce urban heat buildup and air conditioning use by making the roofs of some buildings reduce or reflect heat rather than absorb it. This thermal image shows that City Hall's "green roof" – covered with soil and vegetation – is 77°F cooler than the nearby conventional roofs.



Great Plains

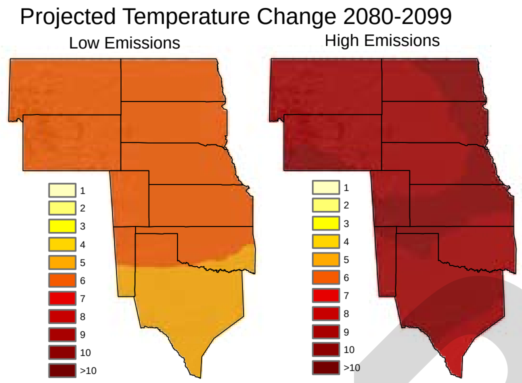


The Great Plains is characterized by strong climate variations. Over thousands of years, records preserved in tree rings, sediments, and sand deposits provide evidence of recurring periods of extended drought (like the Dust Bowl of the 1930s) alternating with wetter conditions[1].

Today, semi-arid conditions in the western Great Plains gradually transition to a moister climate in the east. Temperatures range from very cold in the north, where North Dakota winters average 10°F, to very hot in the south, where West Texas sees more than 100 days per year over 90°F.

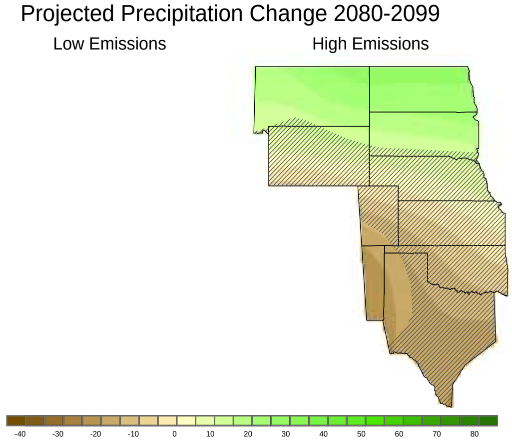
Significant trends in regional climate are apparent over the last few decades. Temperatures have increased throughout the region, with the largest changes occurring in winter months and over the northern states. Extremely cold days are becoming less frequent, and extremely hot days more frequent[2]. Precipitation has also increased over most of the area[3].

Over the coming century, temperatures are projected to continue to increase, with the amount of increase depending on future emissions of heat-trapping gases. By the end of the century, much greater changes are expected under higher emissions than lower, and summer changes are projected to be larger than those in winter. Precipitation is also projected to change, particularly in winter and spring. Conditions are anticipated to become wetter in the north, and drier in the south.

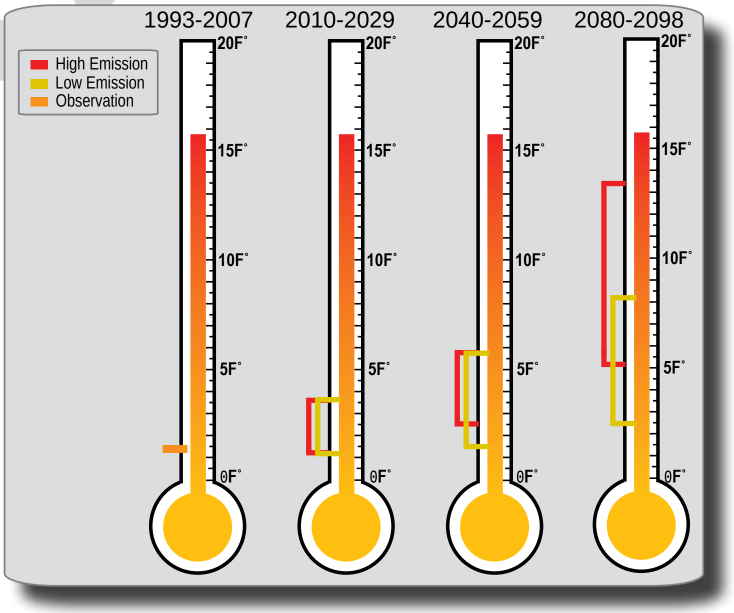


Projected change in summer temperature (°F)

Projected changes in long-term climate and more frequent extreme events such as heat waves, droughts, and heavy rainfall will affect many critical aspects of life in the Great Plains. These include the region's already threatened water resources, essential agricultural and ranching activities, unique natural and protected areas, and the health and prosperity of its inhabitants.



Projected percentage change in spring precipitation. Hatched areas are less certain.



The Dust Bowl: combined affects of human activities and climate

Over the past century, large-scale conversion of grasslands to crop and ranch land has altered the natural environment of the Great Plains. Irrigated fields have increased evaporation rates, reducing summer temperatures and increasing local precipitation[4,5].

The dustbowl of the 1930s is an extreme example of what can happen as a result of interactions between climate and human activity. In the 1920s, increasing demand for food encouraged poor agricultural practices. Small-scale producers ploughed under native grasses to plant wheat, removing the protective cover the land required to retain its moisture. Natural variations in the ocean then caused temperatures to increase slightly, just enough to disrupt the winds that typically draw moisture north from Mexico into the Great Plains. As the intensively tilled soils dried up, topsoil from an estimated 100 million acres of the Great Plains blew across the continent. The dustbowl resulted from natural climate changes, combined with poor land practices[6]. However, it effectively demonstrated the potentially devastating effects of combining climate change and human choices made without consideration of resources. A similar trend is apparent in regional water use.

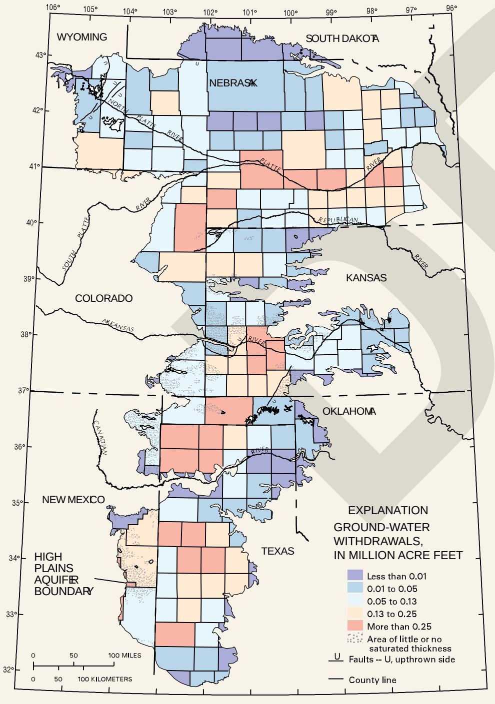
Projections of increasing temperature, evaporation, and drought frequency exacerbate concerns regarding the availability of water in a region dependent on a declining groundwater source.

Water is the most important element affecting activities on the Great Plains. Most of the water used in the Great Plains comes from the High Plains aquifer, which stretches from South Dakota to Texas (Figure 4). The aquifer holds so-called "ancient" water, water trapped by silt and soil washed down from the Rocky Mountains during the last ice age.

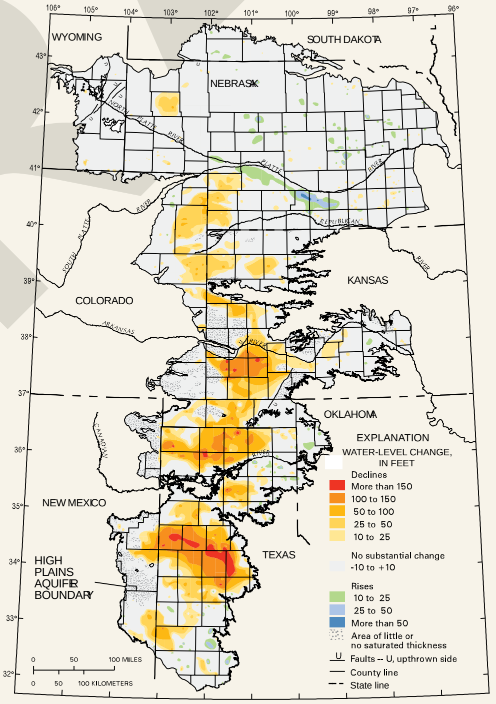
Initially, water from the aquifer was seen as a last resort, to be used only when the rains failed. As irrigation became a way of life in the Great Plains, however, annual withdrawals soon began to outpace natural recharge[7].

Today, an average of 19 billion gallons of ground water are pumped from the aquifer each day. This water irrigates 13 million acres of land and provides drinking water to over 80 percent of the region's population[8]. Since 1950, aquifer water levels have dropped an average of 13 feet. In heavily irrigated parts of Texas, Oklahoma, and Kansas, reductions are much larger, from 100 to over 250 feet.

Groundwater Withdrawals for Irrigation 1950-2005



Water Level Changes in the High Plains Aquifer 1950-2005



Projections of increasing temperatures, faster evaporation rates, and more sustained droughts brought on by climate change will only add more stress to overtaxed water sources. Current water use on the Great Plains is unsustainable, as the High Plains aquifer continues to be tapped at rates greater than it is being recharged.

Agriculture, ranching, and natural lands, already under pressure due to an increasingly limited water supply, will also be stressed by rising temperatures.

The Great Plains is the agricultural heartland of the nation. Range and croplands cover more than 70 percent of the region, producing wheat, hay, corn, barley, cattle, and cotton. Agriculture is fundamentally sensitive to climate. Heat and water stress from droughts, floods, and heat waves can decrease yields and wither crops[9]. The influence of long-term trends in temperature and precipitation can be just as great[10].

As temperatures increase over the coming century, optimal zones for growing particular crops will shift. Pests that were historically unable to survive in the Great Plains' cooler areas are expected to spread northward. Rising carbon dioxide levels in the atmosphere can increase crop growth, but also make some types of weeds grow even faster[11].

Projected increases in precipitation are unlikely to be sufficient to offset decreasing water availability in the Great Plains due to rising temperatures and aquifer depletion. In some areas, there is not expected to be enough water for agriculture to sustain current usage.

With limited water supply comes an increased vulnerability of agriculture to climate change. Further stresses on water supply for agriculture and ranching are likely as the region's cities continue to grow, increasing competition between urban and rural users[12]. The largest impacts are expected in heavily irrigated areas in the southern Great Plains, already plagued by unsustainable water use and greater frequency of extreme heat.

Adaptation Strategies

Successful adaptation will require diversification of crops and livestock, as well as transitions from irrigated to rain-fed agriculture[13,14]. Producers who can adapt to changing climate conditions will likely survive; some may even thrive. Others, without resources or ability to adapt, will lose out.

Climate change is likely to affect native plant and animal species by altering key habitats such as the wetland ecosystems known as prairie potholes or playa lakes.

Ten percent of the Great Plains is protected lands, home to unique ecosystems and wildlife. The region is a haven for hunters and fishermen, with its ample supplies of moose, elk, and deer, goose, quail, and duck, and walleye and bass.

Climate driven changes are likely to combine with human stresses to further increase the vulnerability of natural ecosystems to pests, invasive species, and loss of native species. Changes in temperature and precipitation affect the composition and diversity of native animals and plants through altering their breeding patterns, water and food supply, and habitat availability. In a changing climate, populations of some pests that are better adapted to a warmer climate, such as red fire ants and rodents, are projected to increase[15,16]. Grassland and plains birds, already besieged by habitat fragmentation, could experience significant shifts and reductions in their range[17].

Urban sprawl, agriculture and ranching practices already threaten the Great Plain's distinctive wetlands. Many of these are home to endangered and iconic species. In particular, prairie wetland ecosystems provide crucial habitat for migratory waterfowl and shore birds.

Ongoing shifts in population from rural to urban centers are expected to increase the vulnerability of Great Plains inhabitants to climate change.

Inhabitants of the Great Plains include Native American populations and a rising number of urban dwellers. Though rural populations are declining, there is a long tradition of rural communities. Although farming and ranching remain primary uses of the land – taking up much of the region's geographical area – growing cities provide housing and jobs for more than two-thirds of the population. For everyone on the Great Plains, though, a changing climate and a limited water supply are likely to challenge their ability to thrive, leading to conflicting interests in the allocation of increasingly scarce water resources[12].

Native American communities: The Great Plains is home to 65 Native American tribes. Many reservations already face severe problems with both water quantity and quality – problems likely to be exacerbated by climate change and other human-induced stresses.

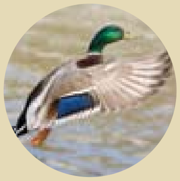
Rural communities: These communities, increasingly populated by a vulnerable demographic of very old and very young, tend to be more at risk for health issues than urban communities. Combined effects of changing demographics and climate are likely to make it more difficult to supply adequate and efficient public health services and educational opportunities to rural areas. Climate-driven shifts in optimal crop types and increased risk of drought, pests, and extreme events will add more economic stress and tension to traditional communities[9,12].

Urban populations: Although the Great Plains is not yet known for its large cities, many mid-sized towns throughout the region are growing rapidly. One in four of the most rapidly growing cities in the nation is located in the Great Plains. Most of these growing centers can be found in the south, where water resources are already challenged. Urban populations, particularly the young, elderly, and economically disadvantaged, may also be disproportionately affected by heat[24].

A number of cities in the Great Plains have identified ways they expect climate change to affect them. Some have designed and begun implementing ways to reduce their community's emissions of heat-trapping gases. For example, Austin, Texas has launched an aggressive campaign to become "carbon neutral" by 2020 through powering all city facilities and vehicles with renewable and alternative energy sources, requiring new housing to use no net energy that emits heat-trapping gases, and initiating community programs to help residents reduce emissions.

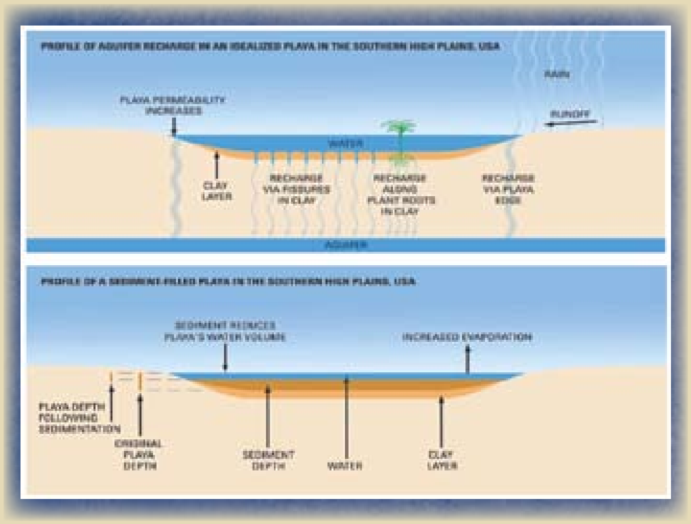
Playa Lakes and Prairie Potholes

Shallow ephemeral lakes dot the Great Plains, anomalies of water in the arid landscape. In the north they are known as prairie potholes, in the south, playa lakes. Playa lakes create unique microclimates that support diverse wildlife and plant communities. A playa can lie with little or no water for long periods, or have several wet/dry cycles each year. When it rains, what appeared to be only a few clumps of short, dry grasses just a few days earlier suddenly teems with frogs and toads, clam shrimp, and aquatic plants.



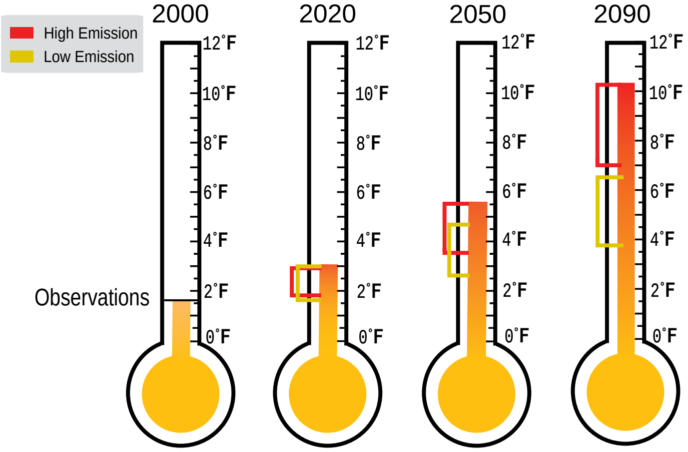
The playas provide a perfect home for migrating birds to feed, mate, and rest. Millions of shorebirds and waterfowl depend on the playas for their breeding grounds, including Canada geese, mallard ducks, and Sandhill cranes. From the prairie potholes of North Dakota to the playa lakes of West Texas, the abundance and diversity of native bird species directly depends on these lakes[18,19].

Despite their small size, playa lakes and prairie potholes also play a critical role in supplying water to the Great Plains. Before cultivation, water from these lakes was the primary source of the recharge to the High Plains aquifer[20]. But many playas are disappearing and others are threatened by growing urban populations, extensive agriculture, and other filling and tilling practices[21]. In recent years, agricultural demands have drawn down the playas to irrigate crops. Agricultural waste and fertilizer residues drain into playas, decreasing the quality of the water, or clogging them so the water cannot trickle down to refill the aquifer. Climate change is expected to add to these stressors, with increasing temperatures and changing rainfall patterns altering rates of evaporation, recharge, and runoff to the playa lake systems[22].



Southwest

The Southwest region stretches from the Pacific Coast to the southern Rocky Mountains. Elevations range from the lowest in the country to among the highest, with climates ranging from the driest to some of the wettest. Past climate records indicate that drought is a normal feature of the Southwest, with some of the longest documented "megadroughts" on Earth. The region has experienced the most rapid population and urban growth since the 1940s, a time with relatively few droughts until quite recently. The prospect for more severe future droughts as a result of global warming is cause for significant concern as the Southwest continues to lead the nation in population growth.



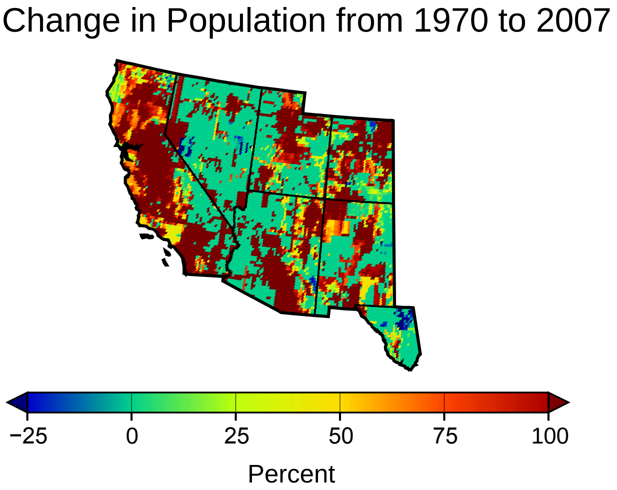
Climate change is well underway in the Southwest. Recent warming is among the most rapid in the nation, and projections suggest continued strong warming, with much larger increases under higher emissions scenarios. For example, summertime increases of up to 18°F are projected by late this century under higher emissions. Such increases will represent significant stresses to health and comfort in a region that already experiences very high summer temperatures. Rising temperatures also portend declining air quality, a particular problem for urban areas, such as those in California which already experience some of the worst air quality in the nation.

Human-induced warming is also causing a decline in spring snowpack and in Colorado River flow[1]. More hydrologic changes are projected, and combined with increasing temperatures, signal a serious drought threat for the region in the decades and centuries ahead.

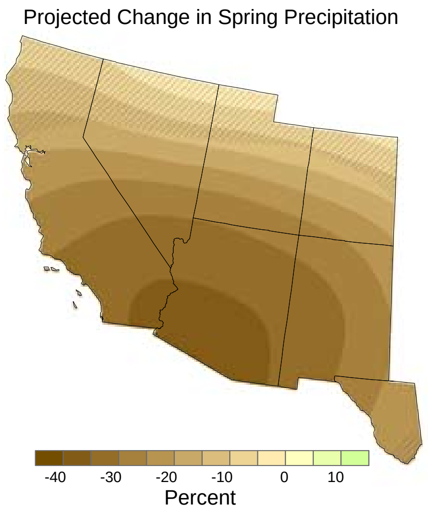
Water supplies will become increasingly scarce, calling for trade-offs among competing uses and potentially leading to conflicts.

Water is needed to support the region's rapid population growth, as well as agriculture, energy, and healthy ecosystems. The largest use of water in the Southwest is associated with agriculture, including some of the nation's most important crop-producing areas in California. Water is also an important source of hydroelectric power, and water is required for the explosive population growth in the region, particularly that of major cities such as Phoenix and Las Vegas. Water also plays a critical role in supporting healthy ecosystems across the region, both on land and in rivers and lakes. Water is, quite literally, the lifeblood of the Southwest.

Water supplies across the Southwest are already becoming more limited, and this trend towards scarcity is a harbinger of future water shortages[2]. Groundwater pumping is lowering water tables and reducing perennial streamflow, just as rising temperatures are reducing the flow in some rivers, including the vital Colorado River[3]. Climate change projections for the rest of this century make it clear that rising temperatures will continue to be the norm, but also that the limitations imposed on water supply by these higher temperatures are likely to be made worse by substantial reductions in rain and snowfall in the all-important spring months[4].



The map above, showing percentage changes in population, shows the very rapid growth in the Southwest. Places with increases over 100 percent growth are shown in maroon. Some of these areas had increases over 500 percent.



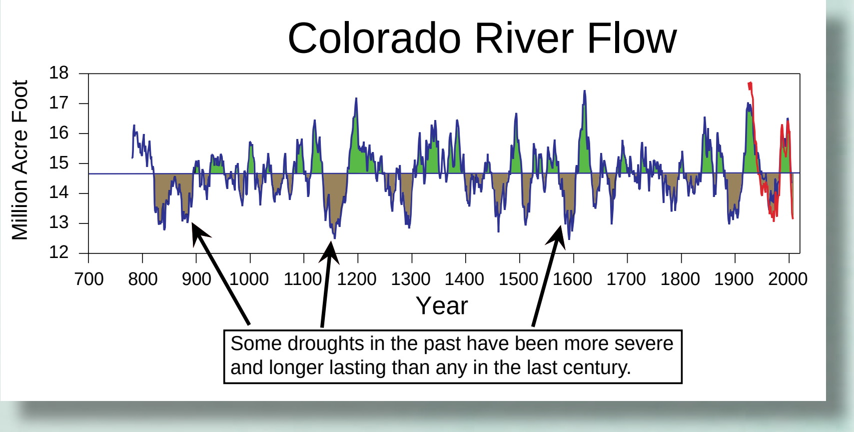
Percentage change in March-April-May precipitation for 2080-2099 compared to 1961-1979 for a higher emission scenario. Hatched areas are less certain.

A warmer and drier future means extra care will be needed in planning the allocation of water for the coming decades. The Colorado Compact, negotiated in the 1920s, allocated the Colorado River's water among the seven basin states, but was based on unrealistic assumptions about how much water was available. Even in normal decades, the Colorado doesn't have enough water to meet allocations, and during droughts, and in the future, the situation looks even bleaker. Water used in agriculture can provide a back-up supply for urban water needs during drought, and non-renewable groundwater can be tapped during dry periods. These water "buffers" are expected to become even more important in the future as climate change dries out the Southwest, yet they are at risk of disappearing as urban populations swell.

Large temperature increases along with river-flow reductions will increase the risk of interstate and bi-national water conflict. Water is already a flashpoint for conflict in the Southwest, and climate change – coupled with rapid population growth – promises to increase the likelihood of water-related conflict. In recent years, negotiations regarding existing water supplies have taken place among the seven states sharing the Colorado River and the two states (New Mexico and Texas) sharing the Rio Grande. Planned lining of major canals to prevent water loss through seepage could result in reduced water supply for those who currently use this "lost" water. Bi-national conflict potential already exists with Mexico in meeting their treaty allocations of Rio Grande and Colorado River water, just as many Native American water settlements have yet to be fully worked out. The specter of a more limited future water supply due to continued climate change and population growth will only make the potential for conflict greater.

Future of Drought in the Southwest

Much of the Southwest remains in a drought that began around 1999. It is the most severe western drought of the last 110 years, made more severe by record warming[5]. Climate projections point to an ever-increasing probability of drought for the region[6,7], and many aspects of these projections, including a northward shift in the jet stream and associated winter-spring storm tracks, are consistent with observed trends over recent decades[8],[9]. Thus, the most likely future for the Southwest is a drier one.



Some droughts in the past have been more severe and longer lasting than any in the last century.

Droughts are a long-standing feature of the Southwest's climate, and the droughts of the last 110 years, including the current on-going drought, pale in comparison to some of the decades-long "megadroughts" that the region has experienced over the last 2000 years[10]. The closing decades of the 1500s were very dry, and during medieval times, even longer – many decades long – droughts gripped parts of the Southwest multiple times[11]. These droughts had clear impacts on the flow of the Colorado River[12,13], the all-important Sierra Nevada headwaters for California[14], and elsewhere. Droughts happen routinely in the Southwest, but what causes a drought to last years, and sometimes decades, is not well understood. This means the Southwest must be prepared for drought, potentially from multiple causes, and that combined effects of natural climate variability and human-induced climate change could turn out to be a "one-two punch" for the region.

Increasing temperature, drought, wildfire, and invasive species will continue to accelerate landscape transformations, and lead to threats to ranching, biodiversity, and protected areas.

Climate change already appears to be influencing natural and managed ecosystems of the Southwest, and future landscape impacts could be substantial. Temperature increases have made the current drought in the region more severe than the more natural droughts of the last several centuries, with implications for natural ecosystems. For example, about 4600 square miles of piñon-juniper woodland in the Four Corners region of the Southwest have witnessed substantial die-offs of piñon pine trees[15]. Record wildfires are also being driven by rising temperatures and related reductions in spring snowpack and soil moisture[16].

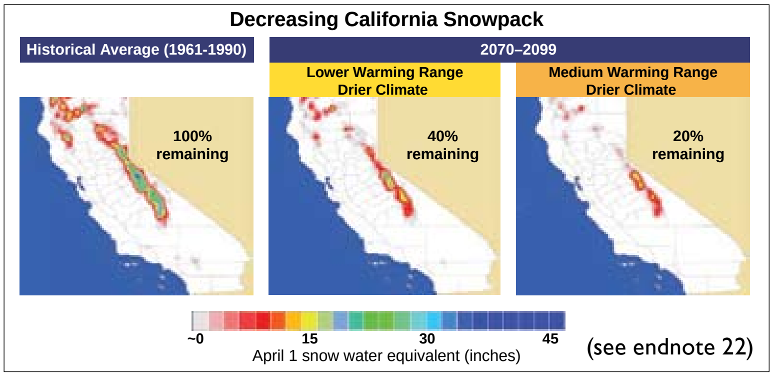
Reduced water levels on the Lake Powell reservoir leave a "bath tub ring" that shows the previous water level.

Climate change, coupled with invasive plant species, have the potential to greatly alter iconic landscapes of the Southwest by making fire a more frequent event in these ecosystems that are not adapted to fire, and thus have no natural defenses against it. For example, the Sonoran Desert, famous for the saguaro cactus, is being invaded by red brome and buffle grasses that do well in high temperatures and are native to Africa and the Mediterranean. Not only do these noxious weeds out-compete some native species in the Sonoran Desert, they also fuel hot cactus-killing fires. Climate warming will also impact the look and feel of the Sonoran Desert in other ways, such as if more woody species spread northward from Mexico into areas currently dominated by native grasses[17]. Both Saguaro and Joshua Tree National Parks, for example, could end up with far fewer of their namesake plants[18].

The Southwest region is also home to two of the world's biodiversity "hotspots" – at-risk regions that hold large numbers of plant and animal species found only in those regions[19,20]. Riparian and wetland ecosystems are home to much of this biodiversity and are already severely compromised by dams and reservoirs, water withdrawals, and invasive species – a situation that will likely worsen as climate change stresses water supply.

Given the mountainous nature of the Southwest, and the great diversity of plants and animals, there are undoubtedly other species that are at risk in the face of climate change combined with other regional threats including human-caused fragmentation of the landscape, invasive species, groundwater and streamflow reductions, and pollution. As plant and animal species change, ranchers, foresters, and others in the Southwest will have to adjust to the rapidly changing landscapes.

Increased frequency and altered timing of flooding, in some cases coupled with landscape transformation, will increase risks to people, ecosystems, and reservoirs.



(see endnote 22)

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Paradoxically, future climate change means not only a greater likelihood of drought for the Southwest, but also an increased risk of flooding. Precipitation patterns are already observed to be shifting, with more rain falling in heavy downpours, the kinds of events that can lead to flooding[21]. Rapid landscape transformation due to vegetation die-off, wildfire, and loss of wetlands along rivers is also likely to reduce the flood-buffering capacity of the region.

Potential impacts of greater flooding obviously include greater risk to humans and human infrastructure, but there are likely to be other impacts as well. Flooding causes reservoirs to fill with sediment at a faster rate, thus reducing their water-storage capacities. The Sacramento-San Joaquin River Delta system is already at substantial risk of flooding, and climate change-related increases in river flooding, coupled with sea level rise, would make the situation worse.

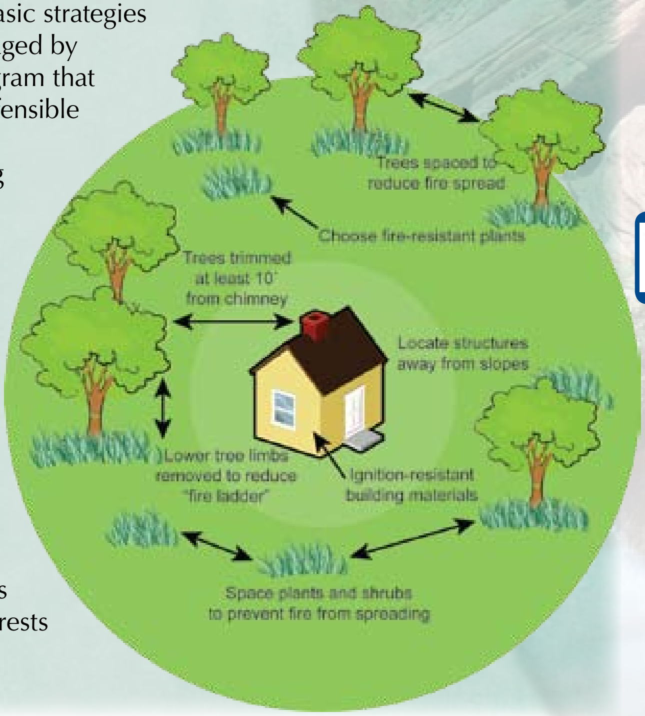
Tourism and recreation are projected to suffer from the impacts of climate change.

Tourism and recreation are important aspects of the region's economy. Winter recreation, notably skiing, is already seeing the affects of warming. The future viability of some ski resorts is threatened by continued climate change, especially under higher emissions scenarios. Ecosystem degradation will affect the quality of the experience for hikers, bikers, birders, and others who enjoy the Southwest's natural beauty. Water sports that depend on the flows of rivers and sufficient water in lakes and reservoirs are already being affected, and much larger changes are expected.

Adaptation Strategies: Fire

Living with the observed and projected increase in fire risk involves actions by residents as well as fire and land management officials. Some basic strategies for reducing damage to structures due to fires are being encouraged by groups like National Firewise Communities, an interagency program that encourages wildfire preparedness measures such as creating defensible space around residential structures by thinning trees and brush, choosing fire-resistant plants, selecting ignition-resistant building materials, positioning structures away from slopes, and working with firefighters to develop emergency plans.

Additional strategies for responding to the increased risk of fire as climate continues to change could include improving evacuation procedures and communications infrastructure. Also important would be regularly updated insights into what the latest climate science implies for changes in types, locations, timing, and potential severity of fire risks over seasons to decades and beyond; implications for related political, legal, economic, and social institutions; and improving prognostications for regeneration of burnt-over areas and the implications for subsequent fire risks. Reconsideration of policies that encourage growth of residential developments in or near forests is another potential avenue for adaptive strategies.

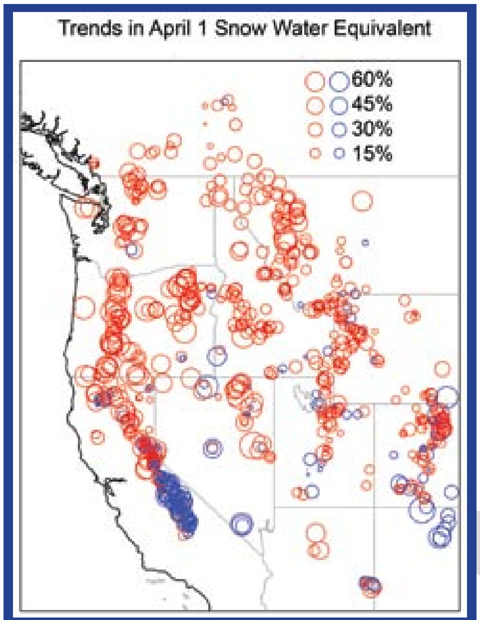


Northwest

The Northwest's rapidly growing population, as well as its forests, mountains, rivers, and coastlines, are already experiencing human-induced climate change and its impacts[1]. Regionally averaged temperature rose about 1.5°F over the past century[2] (with some areas experiencing increases up to 4°F), and is projected to increase another 3 to 10°F in this century[3], with higher emissions scenarios resulting in the upper end of this range. Increases in winter precipitation and decreases in summer precipitation are projected by many climate models, though these projections are less certain than those for temperature. Impacts related to changes in snowpack, streamflows, sea level, forests, and other important aspects of life in the Northwest are already underway, with more severe impacts expected in this century in response to continued and much more rapid warming.

Declining springtime snowpack leads to reduced summer streamflows, straining water supplies.

Placeholder for photos



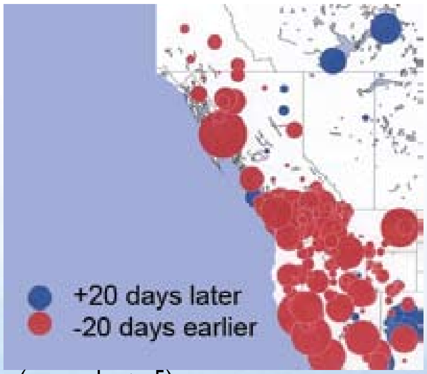
Trends in a common snowpack measurement, for the period 1950–1997. Decreasing trends are in red, increasing trends in blue[3]..

The Northwest is highly dependent on temperature-sensitive springtime snowpack to meet growing, and often competing, water demands such as: municipal and industrial uses, agricultural irrigation, hydropower production, navigation, recreation, and in-stream flows that protect aquatic ecosystems including threatened and endangered species. Higher cool season (October through March) temperatures cause more precipitation to fall as rain rather than snow, and contribute to earlier snowmelt. April 1 snowpack, a key indicator of natural water storage available for the warm season, has already declined substantially throughout the region. The average decline in the Cascade Mountains, for example, was about 25 percent over the past 50 years, with most of this due to the 2.5°F warming in cool season temperatures over that period. Increasing declines in Northwest snowpack are projected to accompany additional warming in this century, varying with latitude, elevation, and proximity to the coast. April 1 snowpack is projected to decline as much as 40 percent in the Cascades by the 2040s[4]. Throughout the region, earlier snowmelt will cause a reduction in the amount of water available during the warm season.

In areas where it snows, a warmer climate means major changes in the timing of runoff: streamflow increases in winter and early spring, and decreases in late spring, summer, and fall. This shift in streamflow timing has already been observed over the past 50 years, with the peak of spring runoff shifting from a few days earlier in some places to as much as 25 or 30 days earlier in others[5].

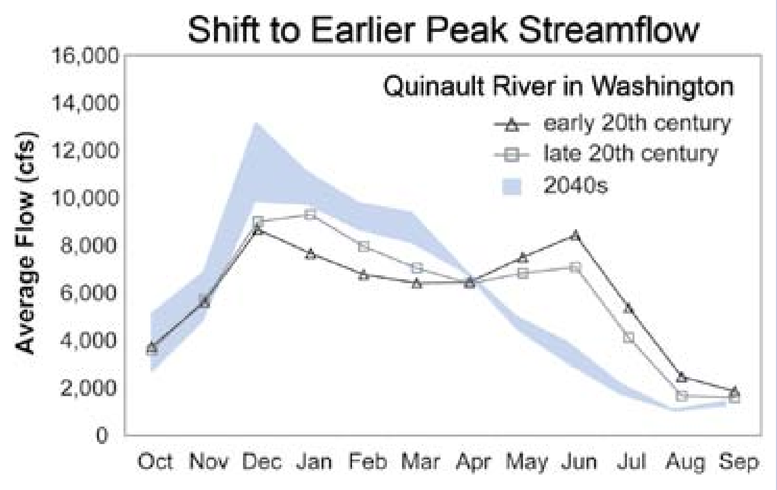
Larger changes are expected due to increased warming, with runoff projected to shift 20 to 40 days earlier in this century[6]. Reductions in summer water availability will vary with midwinter temperatures experienced in different parts of the region. In relatively warm areas on the western slopes of the Cascade Mountains, for example, reductions in warm season (April through September) runoff of 30 percent or more are

Trends in Peak Streamflow Timing



(see endnote 5)

projected by mid-century, whereas colder areas in the Rocky Mountains are expected to see reductions on the order of 10 percent. Areas dominated by rain rather than snow are not expected to see major shifts in the timing of runoff [7]. Extreme high and low streamflows are also expected to change with warming. Increasing winter rainfall (as opposed to snowfall) is expected to increase winter flooding in relatively warm watersheds west of the Cascades. The already low flows of late summer are projected to decrease further due to both earlier snowmelt and increased evaporation and water loss from plants. Projected decreases in summer precipitation would exacerbate these effects. Some sensitive watersheds are projected to experience both increased flood risk and increased drought risk due to warming.



The blue swath represents the range of projected streamflow for 3.6°-5.4°F warming compared to 20th century streamflows[3].

The region's water supply infrastructure was built around the assumption that most of the water needed for summer uses would be stored naturally in snowpack. For example, the storage capacity in Columbia Basin reservoirs is only 30 percent of the annual runoff, and many small urban water supply systems west of the Cascades store less than ten percent of their annual flow[8]. Besides providing water supply and managing flows for hydropower, the region's reservoirs are operated for flood-protection purposes and as such, may have to release (rather than store) large amounts of runoff during the winter and early spring in order to maintain enough space for flood protection. Earlier flows would thus place more of the year's runoff into the category of hazard rather than resource. An advance in the timing of snowmelt runoff would also increase the length of the summer dry period, with important consequences for water supply, ecosystems, and wildfire management[9].

Placeholder for photos

One of the largest demands on water resources in the region is hydroelectric power production. About 70 percent of the Northwest's energy needs are provided by hydropower, far more than in any other region. Warmer summers will increase electricity demands for air conditioning and refrigeration at the same time of year that lower streamflows will decrease hydropower generation. At the same time, water is needed for irrigated agriculture, protecting fish species, reservoir and river recreation, and urban uses. Conflicts between all of these water uses are expected to increase, forcing complex trade-offs between competing objectives[10].

Placeholder for photos

Increased insect outbreaks, wildfires, and changing species composition in forests will pose challenges for unique ecosystems.

Higher summer temperatures and earlier spring snowmelt are expected to increase the risk of forest fires in the Northwest by increasing summer moisture deficits; this pattern has already been observed in recent decades. Drought stress and higher temperatures will decrease tree growth in most low and mid-elevation forests and also increase the frequency and intensity of mountain pine beetle and other insect attacks, further increasing fire risk and reducing timber production, an important part of the regional economy. The mountain pine beetle outbreak in British Columbia has destroyed 33 million acres of trees so far, and shows no signs of slowing (see *Natural Environment and Biodiversity sector* and *Complex Interactions*). Idaho's Sawtooth Mountains are now threatened by pine beetle infestation.

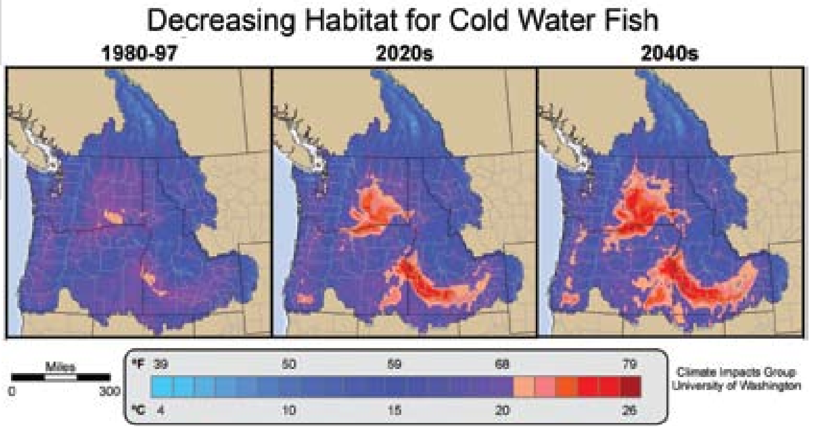
In the short term, high elevation forests west of the Cascade Mountains are expected to see increased growth. In the longer term, forest growth is expected to decrease as summertime soil moisture deficits limit forest productivity, with low-elevation forests experiencing these changes first. The extent and species composition of forests are also expected to change as tree species respond to climatic changes. There is also the potential for extinction of local populations and loss of biological diversity if environmental changes outpace species ability to shift their ranges and form successful new ecosystems.

Agriculture, especially production of tree fruit such as apples, is also an important part of the regional economy. Decreasing irrigation supplies and increased competition from weeds, pests, and disease are likely to have negative effects on agricultural production.

Salmon and other cold-water species experience additional stresses due to rising water temperatures and declining summer streamflows.

Northwest salmon populations are at historically low levels due to stresses imposed by a variety of human activities including dam building, logging, pollution, and over-fishing. Climate change affects salmon throughout their life stages and poses an additional stress. As more winter precipitation falls as rain rather than snow, higher winter streamflows scour the streambed, damaging spawning nests and washing away incubating eggs. Earlier peak streamflows flush young salmon from rivers to estuaries before they are physically mature enough for the transition, increasing a variety of stresses including the risk of being eaten by predators. Lower summer streamflows and warmer water temperatures create less favorable summer stream conditions for salmon and other cold-water fish species in many parts of the Northwest. And diseases and parasites that infect salmon tend to flourish in warmer water. Climate change also impacts the ocean environment, where salmon spend several years of their lives. Historically, warm periods in the coastal ocean have coincided with relatively low abundances of salmon, while cooler ocean periods have coincided with relatively high salmon numbers.

Wild Pacific salmon are mostly extinct or imperiled in 56 percent of their historic range in the Pacific Northwest and California[11], and populations are down more than 90 percent in the Columbia River system. Many species are listed as either threatened or endangered under the Federal Endangered Species Act. Studies suggest that about one-third of the current habitat for the Northwest's salmon and other cold-water fish will no longer be suitable for them by the end of this century as key temperature thresholds are exceeded. Because climate change impacts on their habitat are projected to be negative, climate change is expected to hamper efforts to recover depleted salmon populations.



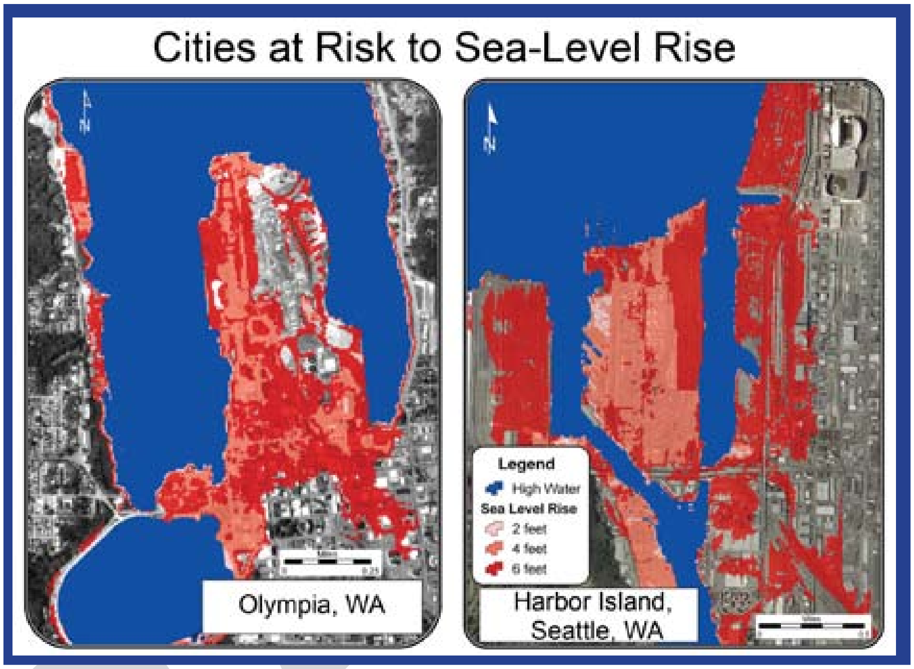
Salmon can be found where average air temperature is less than about 70°F, shown in blue. Projected average August surface air temperatures in the Columbia Basin under a modest warming scenario suggest that salmon are likely to be threatened by rising temperatures across much of their current habitat[3].

Sea-level rise will result in increased erosion along vulnerable coastlines.

Climate change is projected to exacerbate many of the stresses and hazards currently facing the coastal zone. Sea-level rise will increase erosion of the Pacific Northwest coast and cause the loss of beaches and significant coastal land areas. Among the most vulnerable parts of the coast are the heavily populated south Puget Sound region, which includes the cities of Olympia, Tacoma, Seattle, and Bellingham, Washington. Some climate models project changes in atmospheric pressure patterns that suggest a more southwesterly direction of future winter winds. Combined with higher sea levels, this would accelerate coastal erosion on the Pacific coast.

Sea-level rise in the Northwest (as elsewhere) is determined by global rates of sea-level rise, changes in coastal elevation associated with movement of the land locally, and atmospheric dynamics that influence wind-driven “pile up” of sea level along the coast. A medium estimate of sea-level rise for the Puget Sound basin is about 13 inches by 2100. However, higher levels, up to 50 inches by 2100 in more rapidly subsiding portions of the basin are also possible given the large uncertainties about accelerating rates of ice melt from Greenland and Antarctica in recent years[12].

An additional concern is landslides on coastal bluffs. The projected heavier winter rainfall suggests an increase in saturated soils and therefore more landslides. Increased frequency and/or severity of landslides is expected to be especially problematic in areas where there has been intensive development on unstable slopes. Within Puget Sound, the cycle of beach erosion and bluff landslides will be exacerbated by sea-level rise, increasing beach erosion and decreasing slope stability.



(end note 13)

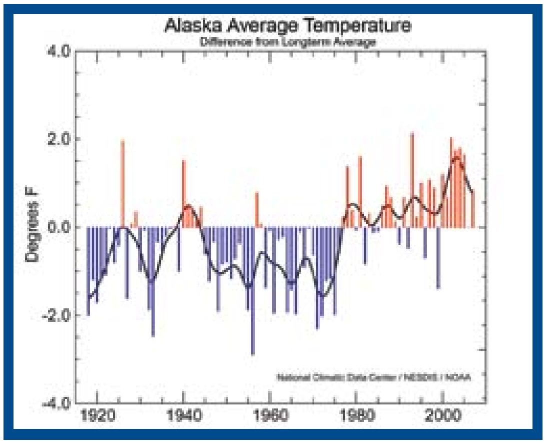
Adaptation Strategies

States, counties, and cities in the Northwest are beginning to develop adaptation strategies to climate change. In 2007, Washington State convened stakeholders to develop adaptation strategies for water, agriculture, forests, coasts and infrastructure, and human health. Recommendations included improved drought planning, improved monitoring of diseases and pests, incorporating sea-level rise in coastal planning, and public education. An implementation strategy is under development.

In response to concerns about increasing flood risk, King County, Washington approved plans in 2007 to fund repairs to the county’s aging levee system. The county will also replace more than 57 “short span” bridges with wider span structures that allow more debris and floodwater to pass underneath without raising river levels. The county has begun incorporating porous concrete and rain gardens into road projects to manage the effects of stormwater runoff during heavy rains, which are increasing due to climate change. King County has also published an adaptation guidebook that is becoming a model for other local governments to organize adaptation actions within municipal planning processes.

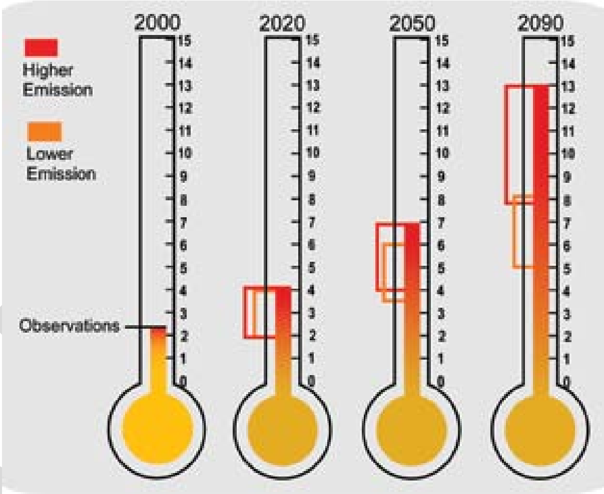
Concern about sea-level rise in Olympia, Washington, contributed to the city’s decision to relocate its primary drinking water source from a low-lying surface water source to wells on higher ground. The city adjusted its plans for construction of a new City Hall to locate the building in an area less vulnerable to sea-level rise than the original proposed location. The building’s foundation was also raised by one foot.

Alaska

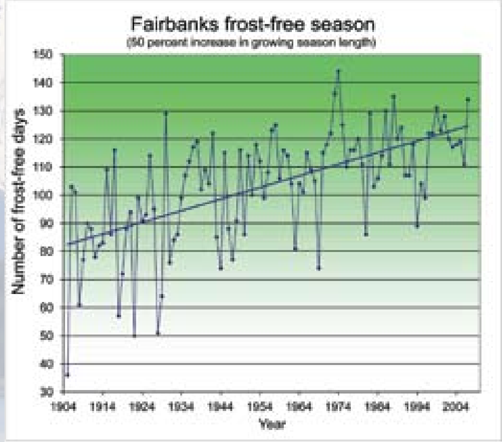


Over the past 50 years, Alaska has warmed at more than twice the rate of the rest of the U.S. Its annual average temperature has increased 3.4°F, while winters have warmed even more, by 6.3°F. As a result, climate change impacts are much more pronounced than elsewhere. The higher temperatures are already causing earlier spring snowmelt, reduced sea ice, widespread glacier retreat, and permafrost warming[1]. These observed changes are consistent with climate model projections of greater warming over Alaska, especially in winter, as compared to the rest of the country.

Climate models also project increases in precipitation over Alaska. Simultaneous increases in evaporation due to higher air temperatures, however, are expected to lead to drier conditions overall, with reduced soil moisture[2]. In the future, therefore, model projections suggest a longer summer growing season combined with an increased likelihood of summer drought and wildfires.

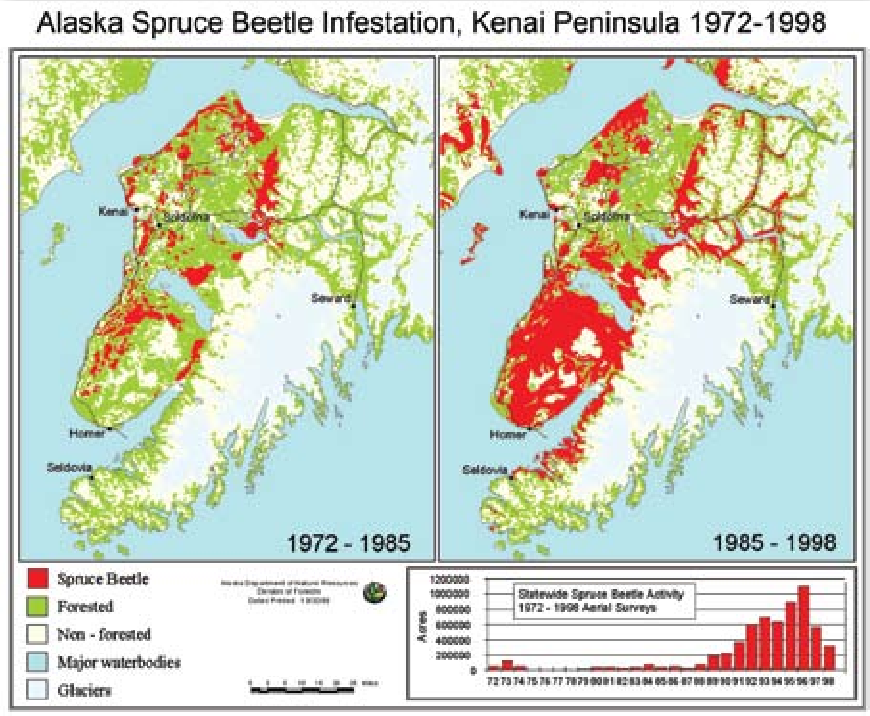


Average annual temperatures in Alaska are projected to rise about 4 to 7°F by the middle of this century. How much temperatures rise later in the century depends strongly on global emissions choices, with increases of 5 to 8°F projected under lower emissions, and increases of 8 to 13°F under higher emissions. Higher temperatures are expected to continue to reduce Arctic sea ice coverage. Reduced sea ice provides opportunities for increased shipping and resource extraction. At the same time, however, it increases coastal erosion, raises the risk of accidents as offshore commercial activity increases, and is expected to drive major shifts of marine species such as pollock and other commercial fish stocks.



Summers are becoming longer and drier.
Between 1970 and 2000, the snow-free season increased by approximately ten days across Alaska, primarily due to earlier snowmelt in the spring[3,4]. A longer growing season has potential economic benefits, providing a longer period of outdoor and commercial activity (such as tourism). There are also downsides, as white spruce forests in Alaska's interior are experiencing declining growth due to drought stress[5] and continued warming could lead to widespread death of trees[6]. The decreased soil moisture in Alaska also suggests that agriculture in Alaska may not benefit from the longer snow-free growing season.

Insect outbreaks and wildfires are increasing with warming.
Climate plays a key role in determining the extent and severity of insect outbreaks and wildfires[7,8]. During the 1990s, for example, south-central Alaska experienced the largest outbreak of spruce bark beetles in the world[9]. This outbreak occurred because rising temperatures allowed the spruce bark beetle to survive over the winter and to complete its life cycle in just one year instead of the normal two years. Healthy trees ordinarily defend



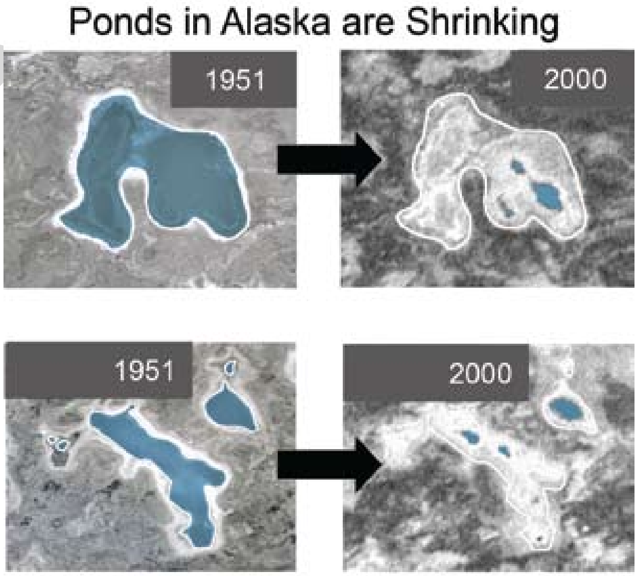
themselves by pushing back against burrowing beetles with their pitch. From 1989 to 1997, however, the region experienced an extended drought, leaving the trees too stressed to fight off the infestation.

Prior to 1990, the spruce budworm was not able to reproduce in interior Alaska[10]. Hotter, drier summers now mean that the forests there are threatened by an outbreak of spruce budworms[11]. This trend is expected to increase in the future if summers in Alaska become hotter and drier[12]. Large areas of dead trees, such as those left behind by pest infestations, are highly flammable and thus much more vulnerable to wildfire than living trees.

The area burned in North America's northern forest that spans Alaska and Canada tripled from the 1960s to the 1990s. Two of the three most extensive wildfire seasons in Alaska's 56-year record occurred in 2004 and 2005, and half of the largest fire years on record have occurred since 1990[13]. Under changing climate conditions, the average area burned per year in Alaska is projected to double by the middle of this century[14]. By the end of this century, area burned by fire is projected to triple in Alaska under a moderate greenhouse gas emissions scenario, and to quadruple under a high emissions scenario. Such increases in area burned would result in numerous impacts, including hazardous air quality conditions such as those suffered by residents of Fairbanks during the summers of 2004 and 2005, as well as increased risks to rural native communities through a reduced ability to hunt, fish, and gather the food that sustains them[15].

Lakes are declining in area.

Across the southern two-thirds of Alaska, the area of closed-basin lakes (lakes without stream inputs and outputs) has decreased over the past 50 years. This is likely due to the greater evaporation and thawing of permafrost that result from warming[16,17]. A continued decline in the area of surface water would present challenges for the management of natural resources and ecosystems on National Wildlife Refuges in Alaska. These refuges, which cover over 77 million acres and comprise 81 percent of the U.S. National Wildlife Refuge System, provide breeding habitat for millions of waterfowl and shorebirds that winter in the lower 48. Wetlands are also important to native peoples who hunt and fish for their food in interior Alaska. Many villages are located adjacent to wetlands that support an abundance of wildlife resources. The sustainability of these traditional lifestyles is thus threatened by a loss of wetlands.



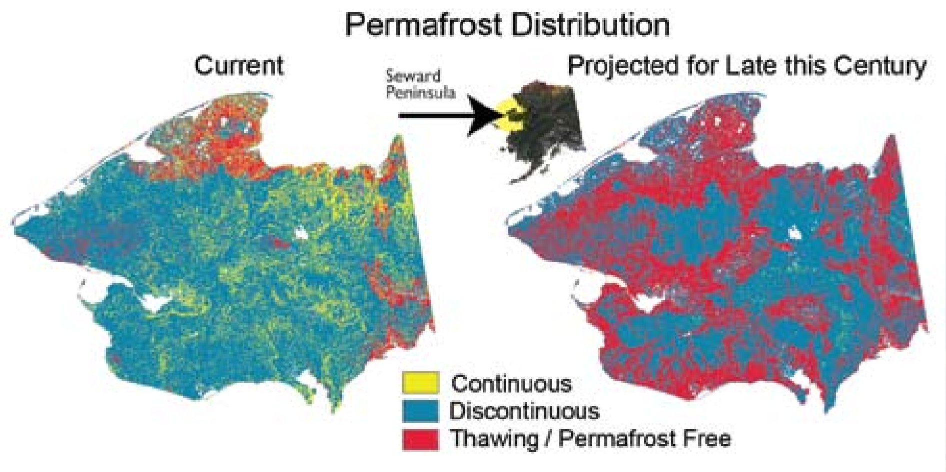
The larger pond in this image shrunk from 90 acres to 4[17].

Thawing permafrost damages roads, runways, water and sewer systems, and other infrastructure.

Permafrost temperatures have increased throughout Alaska since the late 1970s. The largest increases have been measured in the northern part of the state[18]. While permafrost in interior Alaska has so far experienced less warming than permafrost in northern Alaska, it is more vulnerable to thawing during this century because it is generally just below the freezing point, while permafrost in northern Alaska is colder.

The thawing of permafrost presents substantial challenges to engineers attempting to preserve infrastructure in Alaska[19]. Public infrastructure at risk for damage includes roads, runways, and water and sewer systems. It is estimated that thawing permafrost would add between \$3.6 and \$6.1 billion (10 to 20 percent) to future costs for publicly owned infrastructure from now to 2030 and between \$5.6 and \$7.6 billion (10 to 12 percent) from now to 2080[20]. Analyses of the additional costs of permafrost thawing to private property have not yet been conducted.

Thawing ground also has implications for oil and gas drilling. Because of the warming in recent decades, the number of days per year in which travel on the tundra is allowed under Alaska Department of Natural Resources standards has dropped from over 200 to about 100 days in the past 30 years, a 50 percent reduction in days that oil and gas exploration and extraction equipment can be used[21,22].

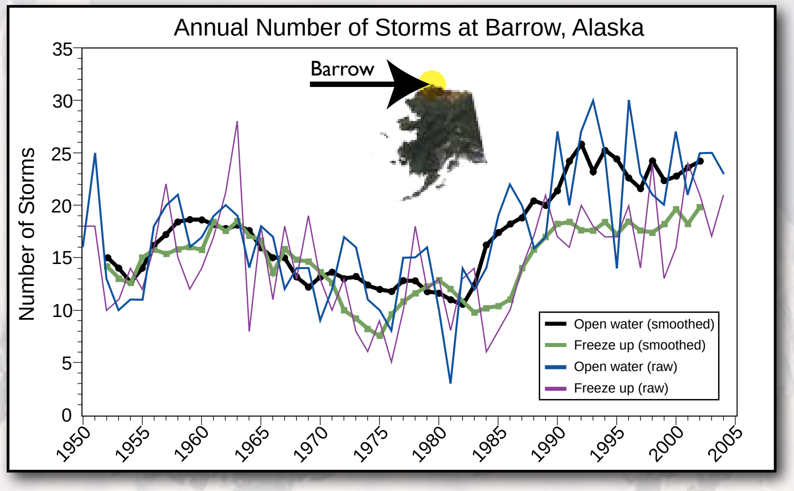


The maps show the extent of thawing projected to occur on Alaska's Seward Peninsula in this century under a moderate warming scenario.

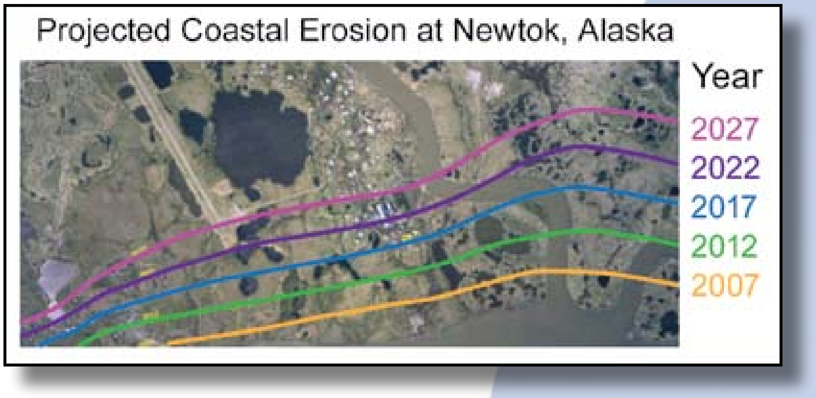
Coastal storms increase risks to villages and fishing fleets.

Alaska has more coastline than the other 49 states combined. Frequent storms in the Gulf of Alaska and the Bering, Chukchi, and Beaufort Seas already affect the coasts during much of the year. Alaska's coastlines, many of which are low in elevation, are increasingly threatened by a combination of the loss of their protective sea ice buffer, increasing storm activity, and thawing coastal permafrost.

Increasing storm activity in autumn in recent years[23] has delayed or prevented barge operations that supply coastal communities with fuel. Commercial fishing fleets and other marine traffic are also strongly affected by Bering Sea storms. High-wind events have become more frequent along the western and northern coasts. The same regions are experiencing increasingly long sea ice-free seasons and hence longer periods during which coastal areas are especially vulnerable to wind and wave



damage. Downtown streets in Nome, Alaska have flooded in recent years. Coastal erosion is causing the shorelines of some areas to retreat at average rates of tens of feet per year. The ground beneath several native communities is literally crumbling into the sea, forcing residents to confront difficult and expensive choices between relocation and engineering strategies that require continuing investments despite their uncertain effectiveness (see *Society* sector).



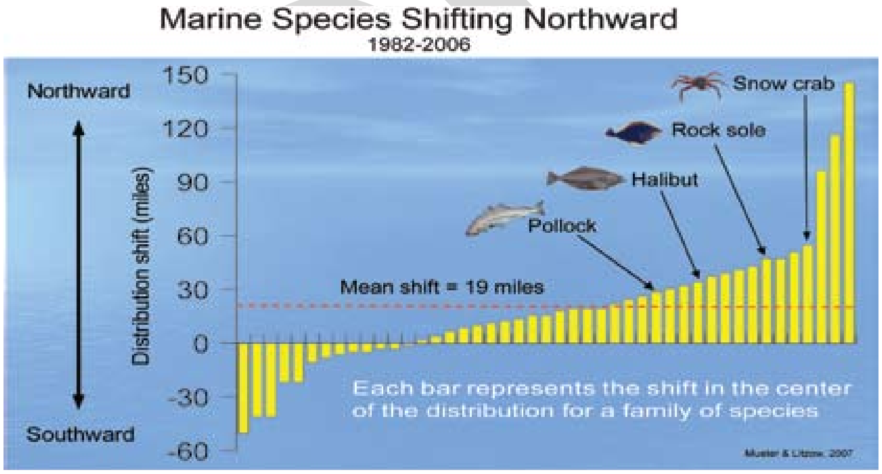
Over the coming century, an increase of sea surface temperatures and a reduction of ice cover are expected to lead to northward shifts in the Pacific storm track and enhanced impacts on coastal Alaska[24,25]. Climate models project the Bering Sea to experience the largest decreases in atmospheric pressure in the Northern Hemisphere, suggesting an increase in storm activity in the region[26]. In addition, the longer ice-free season will make more heat and moisture available for storms in the Arctic Ocean, potentially increasing their frequency and/or intensity.

Displacement of marine species will affect key fisheries.

Alaska leads the United States in the value of its commercial fishing catch. Most of the nation's salmon, crab, halibut, and herring come from Alaska. In addition, many native communities depend on local harvests of fish, walruses, seals, whales, seabirds, and other marine species for their food supply. Climate change causes significant alterations in marine ecosystems with important implications for fisheries. Ocean acidification associated with rising carbon dioxide levels represents an additional threat to cold-water marine ecosystems.

One of the most productive areas for Alaska fisheries is the northern Bering Sea off Alaska's west coast. The world's largest single fishery is the Bering Sea pollock fishery, which has undergone major declines in recent years. Over the past decade, as air and water temperatures rose, sea ice in this region declined sharply. Populations of fish, seabirds, seals, walruses, and other species depend on plankton blooms that are regulated by the extent and location of the ice edge in spring. As the sea ice retreats, the location, timing, and species composition of the blooms is changing, reducing the amount of food reaching the living things on the ocean floor. This radically changes the species composition and populations of fish and other marine life forms, with significant repercussions for fisheries (see *Ecosystems* sector)[27].

Over the course of this century, changes already observed on the shallow shelf of the northern Bering Sea are expected to affect a much broader portion of the Pacific-influenced sector of the Arctic Ocean. As such changes occur, the most productive commercial fisheries are likely to become more distant from existing fishing ports and processing infrastructure, requiring either relocation or greater investment in transportation time and fuel costs. These changes will also affect the ability of native peoples to successfully hunt and fish for the food they need to survive. Coastal communities are already noticing a displacement of walrus and seal populations. Bottom-feeding walrus populations are threatened when their sea ice platform retreats from the shallow coastal feeding grounds on which they depend.



(see endnote 28)

Map for Islands
is still under development

Islands

Climate change presents the Pacific and Caribbean Islands with a unique set of challenges. The U.S. affiliated Pacific Islands are home to approximately 1.7 million people in the Hawaiian Islands; Palau; the Samoan Islands of Tutuila, Manua, Rose, and Swains; and islands in the Micronesian archipelago of the Carolines, Marshalls, and Marianas[1]. These include volcanic, continental, and limestone islands, atolls, and islands of mixed geologies[2]. The degree to which climate change and variability will impact each of the roughly 30,000 islands in the Pacific depends upon a variety of factors, including the island's geology, area, height above sea level, extent of reef formation, and freshwater aquifer size[3].

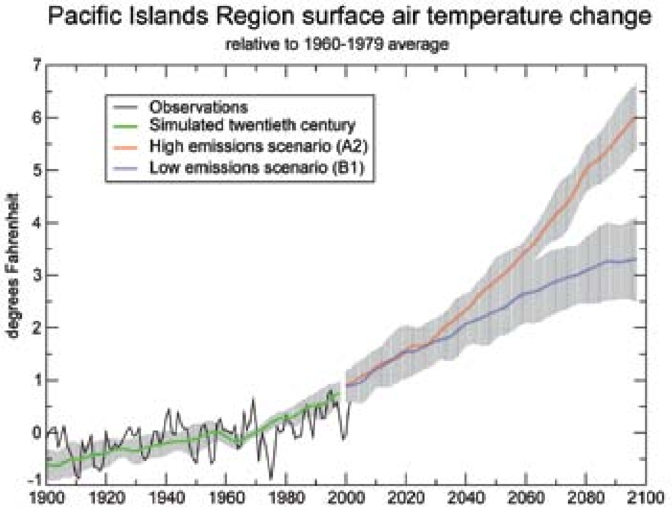
In addition to Puerto Rico and the U.S. Virgin Islands, there are 40 island nations in the Caribbean that are home to approximately 38 million people[4]. Population growth, often concentrated in coastal areas, escalates the vulnerability of both Pacific and Caribbean island communities to the effects of climate change, as does weakened traditional support systems. Tourism and fisheries, which are both climate-sensitive, play a large economic role in these communities[5].

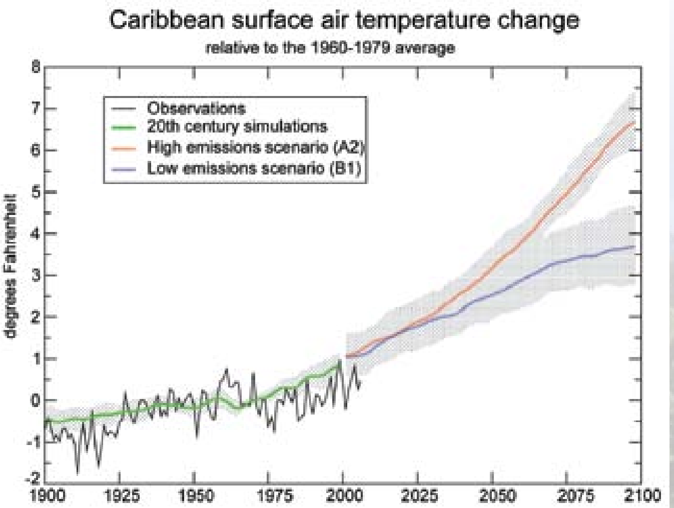
Small islands are considered among the most vulnerable to climate change because extreme events have major impacts on them. Changes in weather patterns and the frequency and intensity of extreme events, sea-level rise, coastal erosion, coral reef bleaching, ocean acidification, and saltwater contamination of freshwater resources are among the impacts small islands face[6].

Islands have experienced rising temperatures and sea levels in recent decades. Projections for the rest of this century suggest:

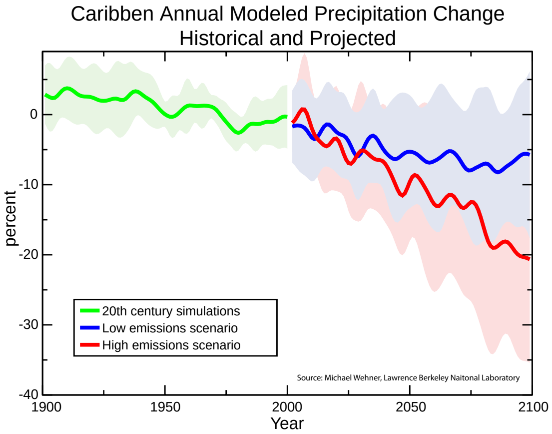
- increases in air and ocean surface temperatures in both the Pacific and Caribbean;
- an overall decrease in rainfall in the Caribbean; and
- an increase in heavy downpours and increased rainfall during summer months (rather than the normal rainy season in winter months) for the Pacific (although the range of projections regarding rainfall in the Pacific is still quite large)

The number of intense storms is likely to increase[7] (hurricanes, typhoons, and heavy rain events). Hurricane (typhoon) wind speeds and rainfall rates are likely to increase with continued warming[8]. Islands and other low-lying coastal areas will be at increased risk from coastal inundation due to sea-level rise and storm surge, with major implications for coastal communities, infrastructure, natural habitats, and resources.

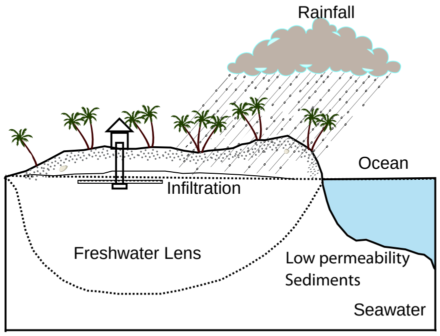




Anticipated reductions in the availability of freshwater will have significant implications for island communities, economies, and resources.



Most island communities in the Pacific and the Caribbean have limited sources of the freshwater needed to support unique ecosystems and biodiversity, public health, agriculture, and tourism. Conventional freshwater resources include rainwater collection, groundwater, and surface water[9]. For drinking and bathing, smaller Pacific islands primarily use individual rainwater catchment systems, while groundwater from the freshwater lens is used for irrigation. The size of freshwater lenses in atolls is influenced by factors such as rates of recharge (through precipitation), rates of use, and extent of tidal inundation[10]. Rainfall is critical, as it triggers the formation of the freshwater lens, and changes in precipitation, such as the significant decreases projected for the Caribbean, can significantly impact the availability of water. Because tropical storms replenish water supplies, potential changes in these storms are of great concern.



Increases in rainfall during the normally dry summer months in the Pacific are likely to result in increased flooding, which reduce drinking water quality and threaten crops[11]. In addition, many islands have weak distribution systems and old infrastructure, which decrease their ability to use freshwater efficiently. Water pollution (*e.g.*, from agriculture or sewage), exacerbated by storms and floods, can contaminate the supply of freshwater, impacting public health. Sea-level rise also impacts island water supplies by causing saltwater to contaminate the freshwater lens,[12] and causing increased frequency of flooding due to storm high tides. Finally, rapidly rising population growth also puts an increasing strain on this limited resource, as would an increased incidence and/or intensity of storms[13] or periods of prolonged drought.

Adaptation Strategies

In the islands, "water is gold." Effective adaptation to climate-related changes in the availability of freshwater is thus of highest priority. While island communities cannot completely counter the threats to water supplies posed by global warming, effective adaptation approaches can help reduce the damage.

When existing resources fall short, managers must consider unconventional resources, such as desalinating seawater, importing water by ship, and using treated wastewater for non-drinking uses. Desalination costs are declining, though concerns remain about the impact on marine life, the disposal of concentrated brines that may contain chemical waste, and the large energy use (and associated carbon footprint) of the process. With limited natural resources, the key to successful water resource management in the islands will continue to be "conserve, recover, and reuse[1]."

A billboard on Pohnpei encourages water conservation in preparation for the 1997-98 El Niño.

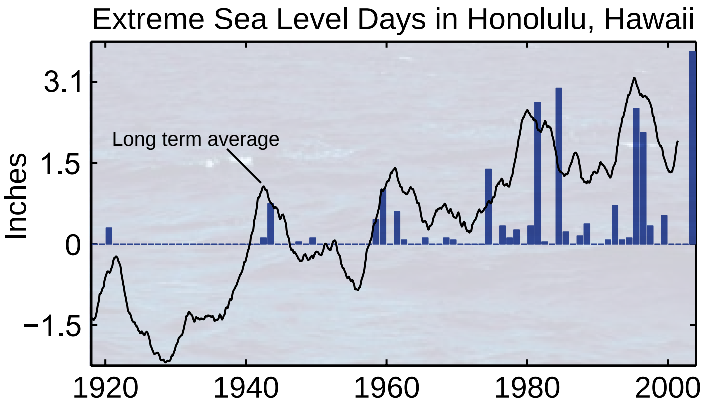
Pacific Island communities are also making use of the latest science, as was done during the 1997/1998 El Niño when managers used seasonal forecasts to prepare for droughts by increasing public awareness and encouraging water conservation. In addition, resource managers can improve infrastructure, such as by fixing water distribution systems to minimize leakage and by increasing freshwater storage capacity[2].

Island communities, infrastructure, and ecosystems are vulnerable to coastal inundation due to sea-level rise and coastal storms.

Sea-level rise will have enormous effects on islands. Flooding will become more frequent due to storm high tides, and coastal land will be permanently lost as the sea inundates low-lying areas and the shorelines erode. This will reduce freshwater supplies[17] and affect living things in coastal ecosystems. For example, the Northwestern Hawaiian Islands, which are low-lying and therefore at great risk from increasing sea levels, have a high concentration of endangered and threatened species, some of which exist nowhere else[18]. The loss of nesting and nursing habitat can threaten the survival of already vulnerable species[19].

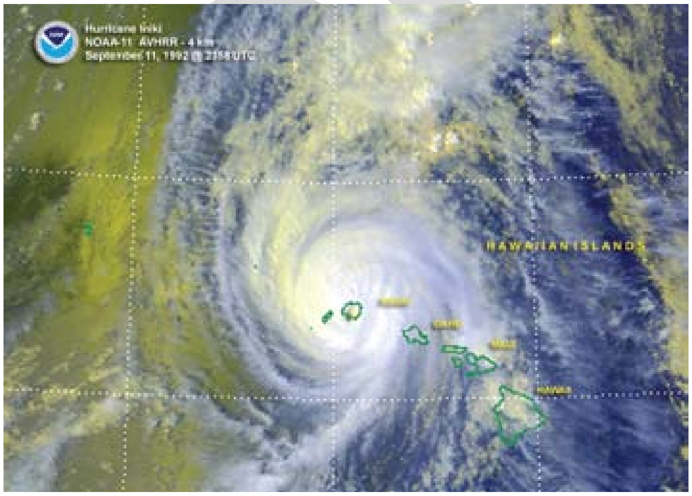
Coastal houses and an airport in the U.S.-affiliated Federated States of Micronesia rely on mangroves' protection from erosion and damage due to rising sea level, waves, storm surges, and wind.

In addition to gradual sea-level rise, extreme high water level events can result from the combination of coastal processes[20]. For example, the harbor in Honolulu, Hawaii experienced the highest daily average sea level ever recorded in September 2003, resulting from the combination of long-term sea-level rise, normal seasonal heating (which causes water to expand and thus rise), and strong swirling winds that raise local sea level in what is called an anticyclonic eddy[21]. The interval between such extreme events has decreased from more than 20 years to approximately five years as average sea level has risen[22].



"Extreme" means a daily average more then 6 inches above the long-term average[24].

Hurricanes, typhoons, and other storm events, with their intense precipitation and storm surge, cause major impacts to Pacific and Caribbean island communities[23], including loss of life, damage to infrastructure and property, and contamination of freshwater supplies. As the climate continues to warm, the number of intense hurricanes and typhoons is likely to increase, with increased peak wind speeds and increased average and peak precipitation intensities[24] causing higher storm surges. If such events occur frequently, communities would face challenges in recovering between events, resulting in long-term deterioration of infrastructure, freshwater and agricultural resources, and other impacts[25].



Critical infrastructure, including homes, airports and roads, tends to be located along the coast. Flooding related to sea-level rise and hurricanes and typhoons negatively impacts port facilities and harbors, and causes closures of roads, airports, and bridges[26]. Long-term infrastructure damage would impact social services such as disaster risk management, health care, education, management of freshwater resources, and economic activity in sectors such as tourism and agriculture.

Climate changes affecting coastal and marine ecosystems will have major implications for tourism and fisheries.

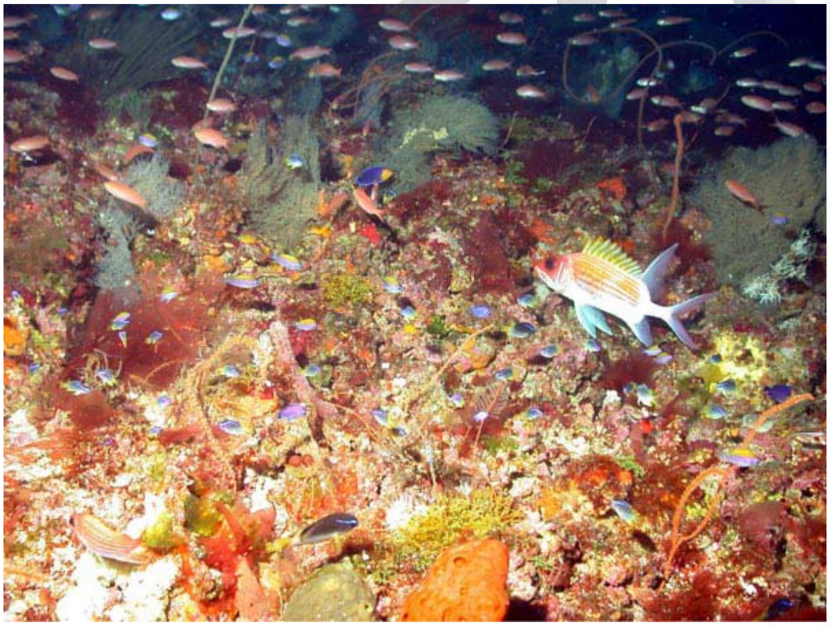
Marine and coastal ecosystems of the islands are particularly vulnerable to the impacts of climate change. Sea-level rise, increasing water temperatures, rising storm intensity, coastal inundation and flooding from extreme events, beach erosion, ocean acidification, and increased invasions by non-native species are among the threats that endanger the ecosystems which provide safety, sustenance, economic viability, and cultural and traditional values to Pacific Island communities[27].

Tourism is a vital part of the economy for many islands. The Caribbean had tourism-based gross earnings of $17 billion in 1999, providing 900,000 jobs, making the Caribbean one of the most tourism dependent regions in the world[28]. In the South Pacific, tourism can contribute as much as 47 percent of gross domestic product[29]. In Hawaii, tourism generated $12.4 billion for the state in 2006, with over seven million visitors[30].

Increasing water temperatures and sea-level rise can erode beaches and destroy or degrade natural resources such as mangroves and coral reef ecosystems which serve as draws for tourists[31]. Extreme weather events can impact transportation systems and interrupt communications. The availability of freshwater is critical to sustaining tourism, but is subject to the climate-related impacts described on the previous page. Public health concerns about diseases such as dengue would also negatively impact tourism.

Coral reefs provide for fisheries and tourism, have biodiversity value, scientific and educational value, and form natural protection against wave erosion[32]. For Hawaii alone, net benefits to the economy are estimated at $360 million annually, and the overall asset value is conservatively estimated to be nearly $10 billion[33]. In the Caribbean, coral reefs provide annual net benefits from fisheries, tourism, and shoreline protection services of between $3.1 billion and $4.6 billion. The loss of income by 2015 from degraded reef is conservatively estimated at several hundred million dollars annually[34].

Coral reef ecosystems are particularly susceptible to the impacts of climate change, as even small increases in water temperature can cause coral bleaching[35], damaging and killing corals. Ocean acidification due to rising carbon dioxide levels poses an additional threat (see *Natural Environment and Biodiversity* sector). Coral reef ecosystems are also especially vulnerable to invasive species[36]. These impacts, combined with changes in the occurrence and intensity of El Niño events, rising sea level, and increasing storm damage[37], will have major negative effects on coral reef ecosystems.



Fisheries feed local people and island economies. Nearly 70 percent of the world's annual tuna harvest, approximately 3.2 million tons, comes from the Pacific Ocean.[38] Climate change is projected to cause a decline in tuna stocks and an eastward shift in their location, impacting the catch of certain countries[39]. For island fisheries sustained by healthy coral reef and marine ecosystems, climate change impacts exacerbate stresses such as overfishing[40], affecting both fisheries and tourism that depend on abundant and diverse reef fish. The loss of live corals results in local extinctions and a reduced number of reef fish species[41].

Coasts

Nearly half of all Americans live in the narrow coastal zone around the United States. In addition to accommodating major cities, the coasts and the exclusive economic zone extending 200 miles offshore provide us enjoyment, recreation, seafood, transportation of goods, and energy. Coastal and ocean activities contribute more than $1 trillion to the nation's gross domestic product and these ecosystems hold rich biodiversity and provide invaluable services[1]. However, intense human uses have taken a toll on coastal environments and their resources. Up to 38 percent of all fish stocks have been diminished by over-fishing, large "dead zones" depleted of oxygen have developed as a result of pollution by excess nitrogen runoff, toxic blooms of algae are increasingly frequent, coral reefs are badly damaged or becoming overgrown with algae, and about half of the nation's coastal wetlands have been lost.

Global climate change poses additional stresses on coastal environments. Rising sea levels are already eroding shorelines, drowning wetlands, and threatening the built environment. The destructive potential of Atlantic tropical storms and hurricanes has increased since 1970 in association with warming Atlantic sea surface temperatures, and it is likely that hurricane rainfall and wind speeds will increase in response to global warming[2]. Coastal water temperatures have risen by about 2°F, and marine species have shifted their geographic distributions[3]. Precipitation increases on land have increased river runoff, bring more nitrogen and phosphorous, sediments, and other pollutants into coastal waters. Furthermore, increasing acidification resulting from the uptake of carbon dioxide by ocean waters threatens corals, shellfish, and other living things that form their shells and skeletons from calcium carbonate[4]. All of these forces converge and interact at the coasts, making these areas particularly sensitive to the impacts of climate change.

Significant sea level rise and storm surge will affect coastal cities and ecosystems around the nation, with low-lying and subsiding areas most vulnerable.

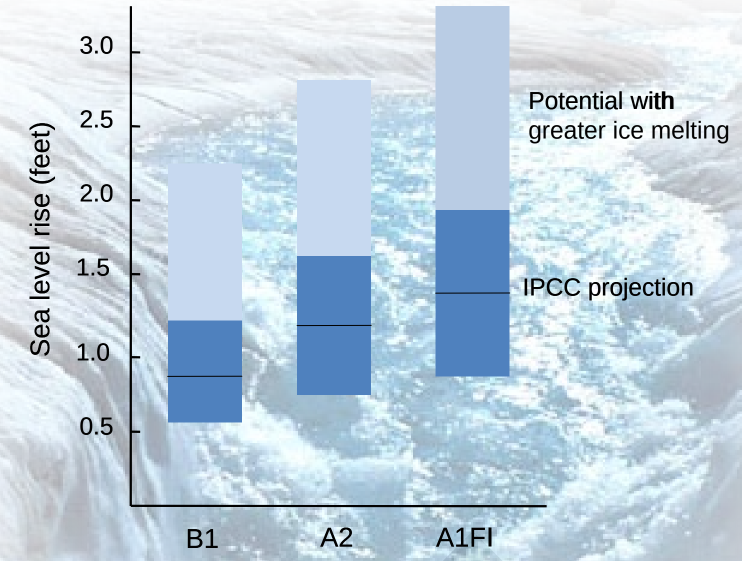
During the past century, the rise in sea level relative to the land ranged from a few inches to two feet, depending on whether and how fast the land was rising or falling. High rates of relative sea level rise, coupled with cutting off the supply of sediments from the Mississippi River and other human alterations, have resulted in the loss of 1,900 square miles of Louisiana's coastal wetlands, weakening their capacity to absorb the storm surge of hurricanes including Katrina[5]. Shoreline retreat is occurring along most of the nation's exposed shores.

"Ghost swamp" in south Louisiana shows the effects of saltwater intrusion

Multiple Stresses Confront Coastal Regions

Various forces of climate change at the coasts pose a complex array of management challenges and adaptation requirements. For example, sea level is likely to rise at least two feet in the Chesapeake Bay, where the land is subsiding, threatening most of the estuaries, tidal wetlands, inhabited islands, and other low-lying regions. Climate change will also affect the volume of the Bay, its salinity distribution, and circulation, as will changes in precipitation and freshwater runoff. These changes, in turn, will affect summer-time oxygen depletion and efforts to reduce the agricultural nitrogen runoff that causes it. Meanwhile the warming of the Bay's waters will make survival there difficult for such northern species as eelgrass and soft clams, while allowing southern species and invaders riding in ships' ballast water to move in and change the mix of species that are caught and must be managed. Additionally, more acidic waters due to rising carbon dioxide levels will make it difficult for oysters to build their shells and will complicate recovery of this key species.

Global sea level rise has been projected to rise 1 to 2 feet during this century,[6] but these estimates purposefully do not include the accelerated melting of the Greenland and West Antarctic ice sheets that many scientists think is likely to occur. Several recent projections suggest that sea level rise by the end of this century could be 3 to 5 feet, especially in subsiding coastal areas[7]. Sea level rise of over 1 foot relative to the land surface is very likely to result in the loss of a large portion of the nation’s remaining coastal wetlands, as they are not able to build new soil at a great enough rate[8]. It would also fragment barrier islands and place into jeopardy many existing homes, business, and infrastructure, including roads, ports, and water and sewage systems. Portions of major cities, including Boston and New York, would be subject to inundation by ocean water during storm surges or even during regular high tides[9].

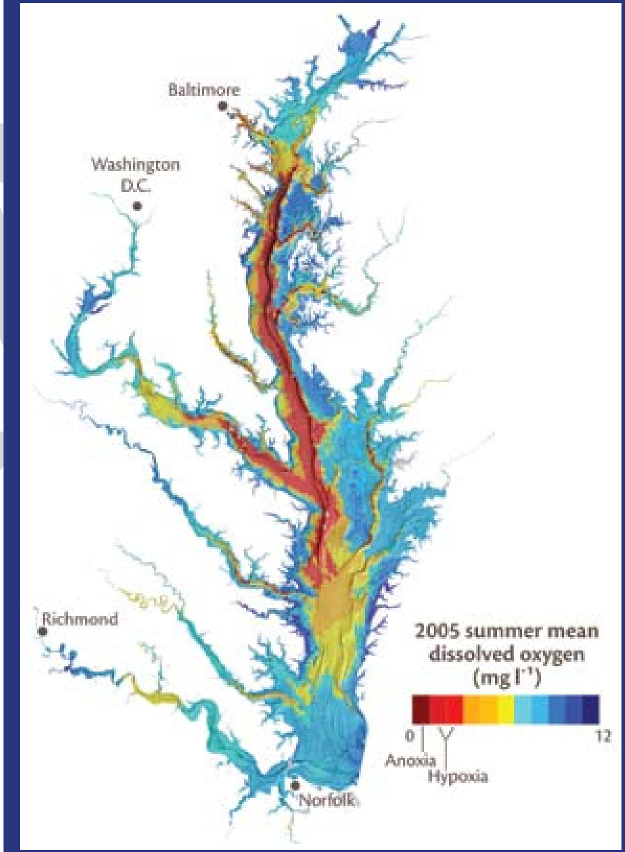


Sea-level rise projections by the end of the century for three emissions scenarios. Land subsidence would increase these rates locally, for example by 0.5 feet in the Chesapeake Bay to 1.5 feet or more along portions of the Gulf Coast. Even greater sea level rise could be realized with greater melting of glaciers and ice sheets.

Increases in spring runoff and warmer coastal waters will exacerbate the seasonal reduction in oxygen resulting from excess nitrogen from agriculture.

Coastal dead zones in places like the northern Gulf of Mexico[10] and the Chesapeake Bay[11] are likely to increase in size and intensity as warming increases, unless efforts to control runoff of agricultural fertilizers are redoubled. Greater spring runoff into east coast estuaries and the Gulf of Mexico would flush more nitrogen into coastal waters stimulating harmful blooms of algae and the excess production of microscopic plants that settle near the sea floor and deplete oxygen supplies as they decompose. In addition, greater runoff reduces salinity, which when coupled with warmer surface water increases the difference in density between surface and bottom waters, thus preventing the replacement of oxygen in the deeper waters. As dissolved oxygen levels decline below a certain level, living things cannot survive. They leave the area if they can, and die if they can’t.

Chesapeake Bay “Dead Zone”



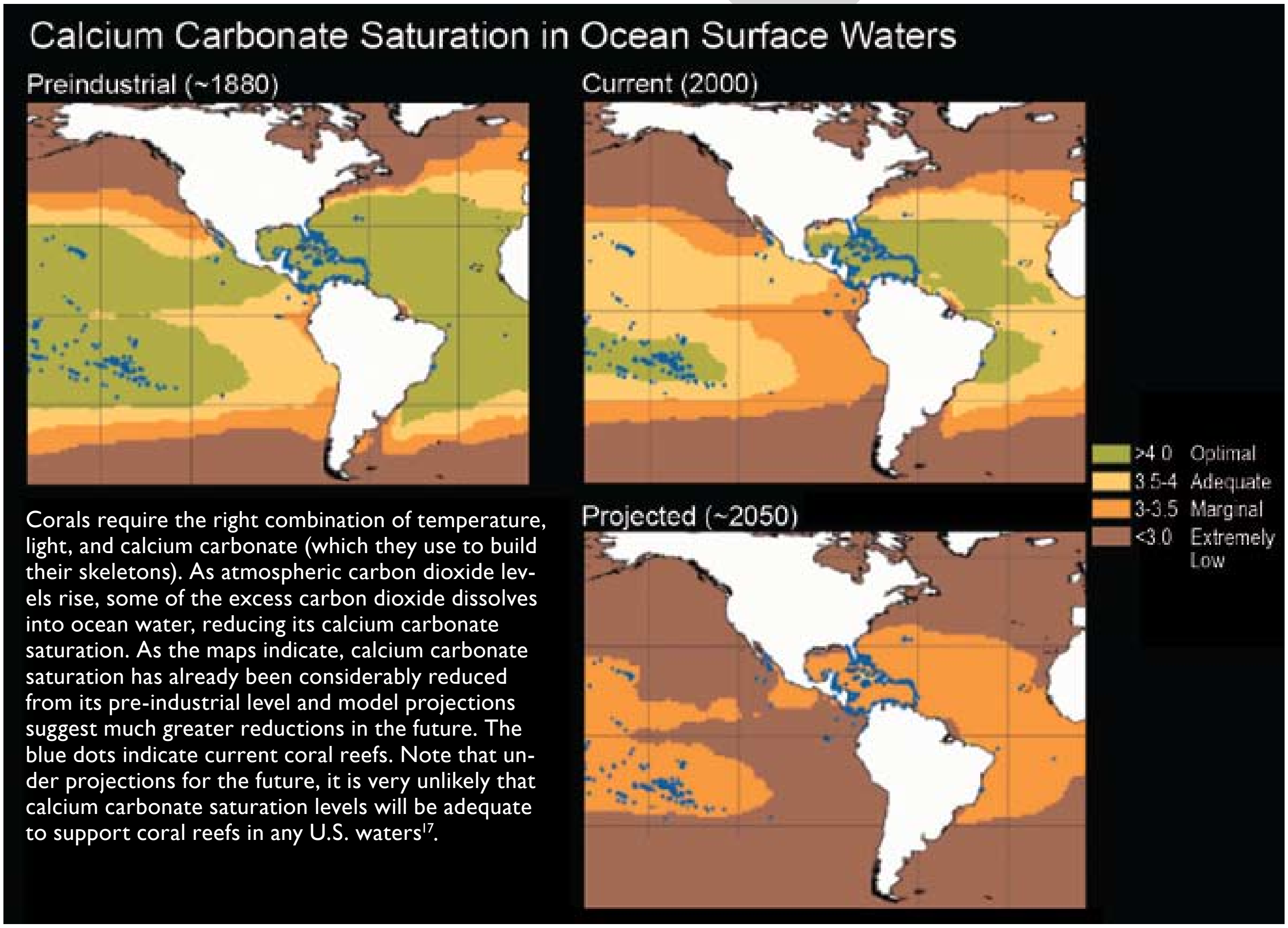
Climate change is likely to exacerbate “dead zones,” areas where bottom water is depleted of dissolved oxygen because of nitrogen pollution, such as this example from Chesapeake Bay.

Warming coastal waters will allow new invasions by non-native species that occur through ship transport and other human activities.

Coastal waters are very likely to continue to warm by as much 4-8°F in this century, both in summer and winter. As with animals and plants on land, this will result in a northward shift in the geographic distribution of marine life along the coasts; this is already being observed.[12] Species that cannot tolerate the higher temperatures will move northward while species from further south move in. This opens the door to invasion by species that humans are intentionally or unintentionally transporting around the world, for example in the ballast water carried by ships. Species that were previously unable to establish populations because of cold winters are likely to find the warmer conditions more welcoming and gain a foothold, particularly as native species are under stress from climate change and other human activities. Nonnative clams and small crustaceans have already had major effects on the San Francisco Bay ecosystem and the health of its fishery resources.[13]

Rising water temperatures and ocean acidification due to increasing atmospheric carbon dioxide present major additional stresses to coral reefs, resulting in significant die-offs and limited recovery.

In addition to its heat-trapping effect, the increase in the concentration of carbon dioxide in the atmosphere is gradually acidifying, or lowering the pH, of the ocean. Much of the carbon dioxide emitted by human activities is absorbed by the ocean. When this carbon dioxide dissolves in sea water it decreases the pH. Since the beginning of the industrial era, ocean pH has declined



Corals require the right combination of temperature, light, and calcium carbonate (which they use to build their skeletons). As atmospheric carbon dioxide levels rise, some of the excess carbon dioxide dissolves into ocean water, reducing its calcium carbonate saturation. As the maps indicate, calcium carbonate saturation has already been considerably reduced from its pre-industrial level and model projections suggest much greater reductions in the future. The blue dots indicate current coral reefs. Note that under projections for the future, it is very unlikely that calcium carbonate saturation levels will be adequate to support coral reefs in any U.S. waters[17].

considerably and is projected to decline much more by 2100 if current emissions trends continue. Such a decline in pH is very likely to affect the ability of organisms to create shells or skeletons of calcium carbonate because lowering the pH decreases the concentration of the carbonate ions required. The living things affected include not only important plankton species in the open ocean, mollusks and other shellfish, but reef-building corals. Acidification imposes yet another stress on these corals, which are also subject to bleaching – the expulsion of the microscopic plants that live inside the corals and are essential to their survival – as a result of heat stress (see *Natural Environment and Biodiversity* sector and *Islands* region). As a result of these and other stresses, the corals that form the reefs in the Florida Keys, Puerto Rico, Hawaii, and the Pacific Islands are projected to be lost if carbon dioxide concentrations continue rising on their current path[14].

Changing coastal currents will result in shifts in fisheries and cause surprising changes such as oxygen-depleted waters that either kill marine species or cause them to leave the area.

Because it affects the distribution of heat in the atmosphere and the oceans, climate change will affect the currents that move along the coast, such as the California Current that bathes the west coast from British Columbia to Baja California. This southward flowing current produces upwelling of deeper ocean water along the coast that is vital to moderation of temperatures and the high productivity of Pacific Coast ecosystems. Such coastal currents are subject to periodic variations caused by the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, which have substantial effects on the success of salmon and other fishery resources. Climate change is expected to impact such coastal currents, and possibly the larger scale natural oscillations as well, though these effects are not yet well understood. The recent emergence of oxygen-depletion events on the continental shelf off Oregon and Washington – a dead zone not directly caused by agricultural runoff and waste discharges like those in the Gulf of Mexico or Chesapeake Bay – may be one such surprise[15].

Location of the Pacific Northwest low oxygen “dead zone” in September of 2006.

Adaptation Strategies

Adaptation to sea level rise is already taking place in three main categories: 1) building hard structures like levees and seawalls, 2) soft protection like enhancing wetlands and adding sand from elsewhere to beaches (not a permanent solution, and can encourage development in vulnerable locations), and 3) accommodating the inland movement of the coastline through planned retreat.

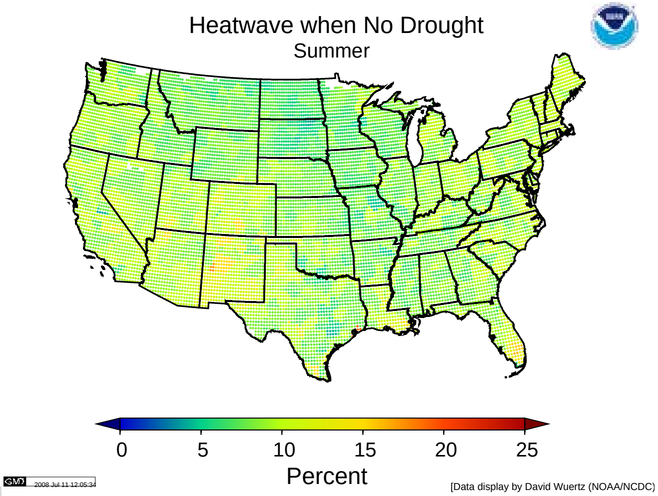
A number of states have laws or regulations that require setbacks for construction that vary based on the life of the development and observed erosion rates. Michigan, North Carolina, Rhode Island, and South Carolina use such a moving baseline to guide planning. Maine’s Coastal Sand Dune Rules prohibit buildings of a certain size that are unlikely to remain stable with a sea level rise of 2 feet. The Massachusetts Coastal Hazards Commission is preparing a 20-year infrastructure and protection plan to improve hazards management and the Maryland Commission on Climate Change has recently made comprehensive recommendations to reduce the state’s vulnerability to sea-level rise and coastal storms by addressing building codes, public infrastructure, zoning, and emergency preparedness. Governments and private interests are beginning to take sea level rise into account in planning levees and bridges, and in the siting and design of facilities such as sewage treatment plants (see Northeast region).

Complex Interactions

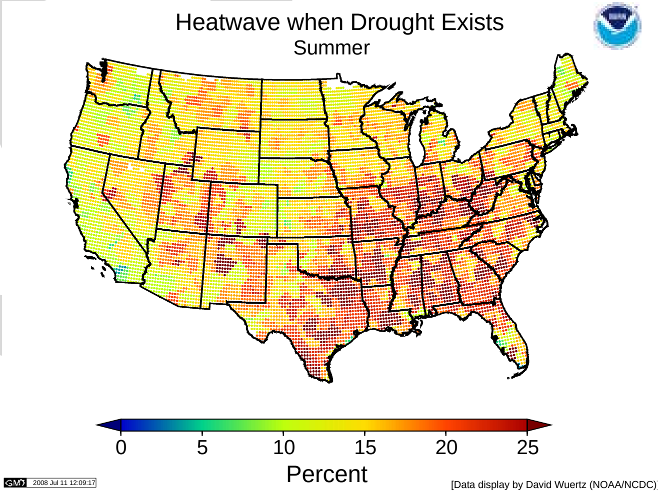
Climate change and its impacts do not occur in isolation. Rather, they interact with each other and with many other factors, resulting in impacts that can be much greater than those due to any of these factors individually. In some cases, key thresholds can be crossed, causing very large-scale and/or irreversible impacts, such as the extinction of species or elimination of entire ecosystems. In some cases, the results of complex interactions can be entirely unexpected. Some examples of such complex interactions are already being observed and the resulting impacts are expected to increase as warming proceeds.

Droughts, heatwaves, and stagnant air

Research has shown that heatwaves and poor air quality often occur simultaneously and in combination with other extreme events such as drought. One of the most costly and prolonged periods of drought, excessive heat, and poor air quality occurred during the summer of 1988. More than 7,000 deaths and economic losses of more than $70 billion were estimated to have occurred in the U.S. due to extreme drought and excessive heat that year. Half of the nation was affected by drought, and 5,994 all-time high temperature records were set around the country in June, July, and August. Poor air quality contributed to the many deaths that occurred, as lack of rainfall, high temperatures, and stagnant conditions led to an unprecedented number of unhealthy air quality days throughout large parts of the country. Although the Environmental Protection Agency (EPA) air quality standard for tropospheric ozone (smog) was less stringent in 1988 than it is today, the poor air quality in many of the nation's city was reflected in hundreds of incidents in which areas exceeded the EPA standard designed to protect the public health.



[Data display by David Wuertz (NOAA/NCDC)]



[Data display by David Wuertz (NOAA/NCDC)]

Long-lasting and extreme events such as these occurring simultaneously can lead to tremendous economic losses and loss of life. The likelihood that such episodes will occur in the future increases as the climate continues to warm. Although heatwaves, drought, and poor air quality can occur independently, experience and research have shown that these events are interrelated. Atmospheric conditions that lead to the presence of one of these often produce another, and the presence of one can contribute to the occurrence of another.

Climate observations bear this out. The maps show the percentage of time since 1950 that summer heatwaves have occurred without drought present and when drought was present[1]. The occurrence of heatwaves was

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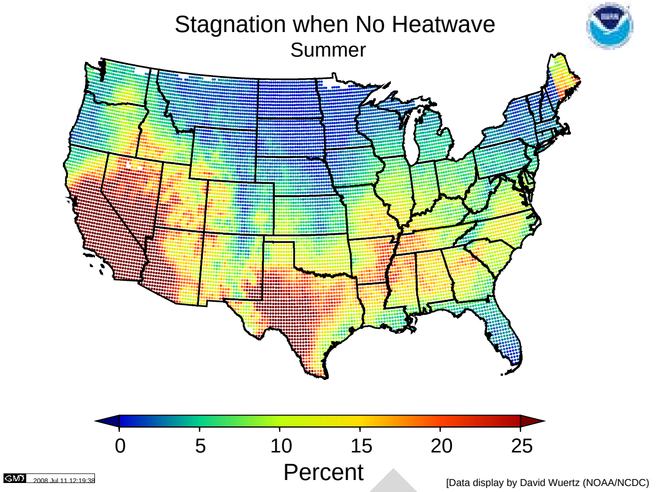
[1] Heatwave conditions were defined as any day when the maximum temperature exceeded that of the 90th percentile of all days. Drought was defined by a monthly Palmer Drought Severity Index of less than -2.

clearly higher in all regions of the contiguous U.S. in the presence of drought, exceeding 20% in large parts of the Midwest, Southeast, southern Plains, and parts of the Southwest, and greater than 10% in most other areas.

Atmospheric conditions that produce heatwaves also often lead to stagnant air masses and poor air quality. While heatwaves and poor air quality threaten the lives of thousands of people each year, the simultaneous occurrence of these hazards compounds the threat to vulnerable populations such as the elderly, children, and people with asthma. The maps show the frequency of occurrence of stagnant air conditions without heatwaves and when heatwave conditions were also present. Although stagnant air occurs more than 25 percent of the time in parts of the South and West, even in the absence of excessive heat, a far larger part of the United States is affected by stagnant air when heatwaves are present. Since 1950, air stagnation and heatwaves have simultaneously occurred more than 25 percent of the time from the mid-Atlantic to the Deep South, southern Plains and across most of the West.



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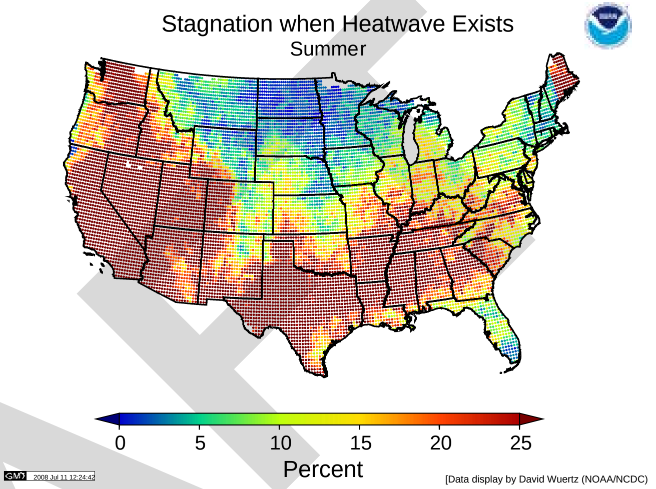

[Data display by David Wuertz (NOAA/NCDC)]

As planning for adaptation to climate change proceeds, it is important to consider all of these factors. For example, in assessing air conditioning demand, projections of heat waves will be important in shaping peak electricity demand. When considering power plants[2], cooling water needs, the potential for drought should be taken into consideration. But we also must realize that during drought when cooling water is at its lowest is often the time when electricity demand for cooling due to a heat wave will be at its highest.

California wildfires that degrade air quality are exacerbated by heat-waves and drought.

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[2] The frequency of occurrence of stagnant conditions was defined as any day that was part of a 4-day air stagnation event. Heatwave conditions were defined as any day when the maximum temperature exceeded that of the 90th percentile of all days.

Bark Beetle Infestations

Another example of complex interactions between changes in climate and other factors is that of insect infestations that are reaching levels that seriously damage the health of forests and cause significant economic losses. The combination of insects and disease in forests has been estimated to cost approximately $1 billion per year, on average, in the U.S. alone.

While large, periodic outbreaks of insects are a natural part of many U.S. forests, these phenomena are taking on new dimensions, and have grown substantially in both extent and severity due to several interacting causes, including long-term changes in climate. Perhaps the best-studied example is the current infestation of pine bark beetles in both the Canadian province of British Columbia and in the Colorado Rocky Mountains.

The mountain pine bark beetle is a native species in mid-elevation lodgepole pine forests throughout the West. Its periodic outbreaks are important features of the overall life cycle of these ecosystems, providing periodic disturbances that open up the canopy for regeneration of seedlings. But throughout the West, there are now three concurrent trends that have affected the way in which the bark beetle interacts with the forest.

Many stands of trees are composed of relatively even-aged trees, most of which are large, mature, and already past their period of rapid growth. This is a consequence of land-use history, specifically the history of logging throughout the region in the late 1800s and 1900s. Trees of this age and size are highly favored by the beetles as hosts, rather than young, rapidly growing trees.

Summers have warmed throughout the region, and there have been increasing periods of drought. The water stress experienced by the trees, both from the direct effects of higher temperatures, and indirectly through earlier snowmelt and reduced availability of water later in the year, are known to increase the susceptibility of the trees to insect attack.

Winter temperatures have also increased, permitting a much higher fraction of the insect larvae to survive the winter. Larvae of the beetle over-winter under the bark of the lodgepole pine, and temperatures of -40˚F for several days are required to kill them off and reduce the numbers of emerging insects the following spring. However, such extremely cold temperatures have become much less frequent in recent decades throughout the mountain West, with the result that many more insect larvae live through the winter.

The net result of these interacting factors is that mountain pine bark beetles have infested and killed lodgepole pines in historically unprecedented numbers and in overall area affected. Over 33 million acres of forest in Canada have been affected, and at least another 620,000 acres in Colorado in the U.S. Mortality of affected lodgepole pine stands has approached 90% of the trees. There is now evidence that the spread of the beetles has crossed the continental divide, which was previously thought to be a natural barrier to their dispersal, but appears now to have been overwhelmed by the insects' sheer numbers. There is even evidence in Canada that the beetles have begun attacking another host species, jack pine, which is one of the characteristic conifers of the southern boreal forest, the range of which extends to the Atlantic Ocean.

Just as the causes of these massive pine bark beetle infestations have multiple dimensions, so do the consequences. There are obvious physical consequences to the ecosystems. The massive, nearly synchronous death of trees raises fire risk while the dried needles are still on the trees. Even if fire does not immediately result, once the needles drop, there are significant changes in the amount of solar energy that reaches the surface and heats the soil, and there are also large changes in the amount of water intercepted and held in the forest ecosystem. In addition, large areas of forest that were once suitable habitat for wildlife are no longer suitable, potentially leading to significant changes in local species.

In addition to these ecological consequences are social and economic consequences for many communities in the West. Especially in British Columbia, these forests are economically valuable for timber and pulp, and the damage from the beetle infestation has had serious negative economic consequences for both forest product companies and the local communities that depend on forest resources for employment and income.

Additional discussions of insect infestations appear in the *Alaska* region and the *Natural Environment and Biodiversity* sector.

Response Strategies Revisited: focus on Adaptation

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Throughout this report, examples of adaptation have been highlighted. However, the costs and benefits of various strategies have received little attention to date, and the actual pursuit of such strategies is still in its infancy in most cases.

Planning for and adapting to climate change is an evolutionary process. Through adoption of longer planning horizons, risk management, and adaptive responses, vulnerable infrastructure can be made more resilient, maintaining critical services in the face of climate stressors.

Insurance and Adaptation

Insurance is an arena where adaptation is receiving some attention. For example, some insurance companies have issued guidelines that help reduce losses due to extreme weather events. The insurance company FM Global reports that 310 commercial locations worth $24.4 billion in the path of Hurricane Katrina that had implemented all of its recommended hurricane-loss-prevention methods reduced their losses by 85 percent compared to those that had not done so. These benefits came at a bargain, with $480 million in losses avoided as a result of customer investments of only $2.3 million. The average cost of the risk reduction measures was approximately $7,400 per site on average. FM Global was one of the most profitable U.S. insurers during the year of Hurricane Katrina.

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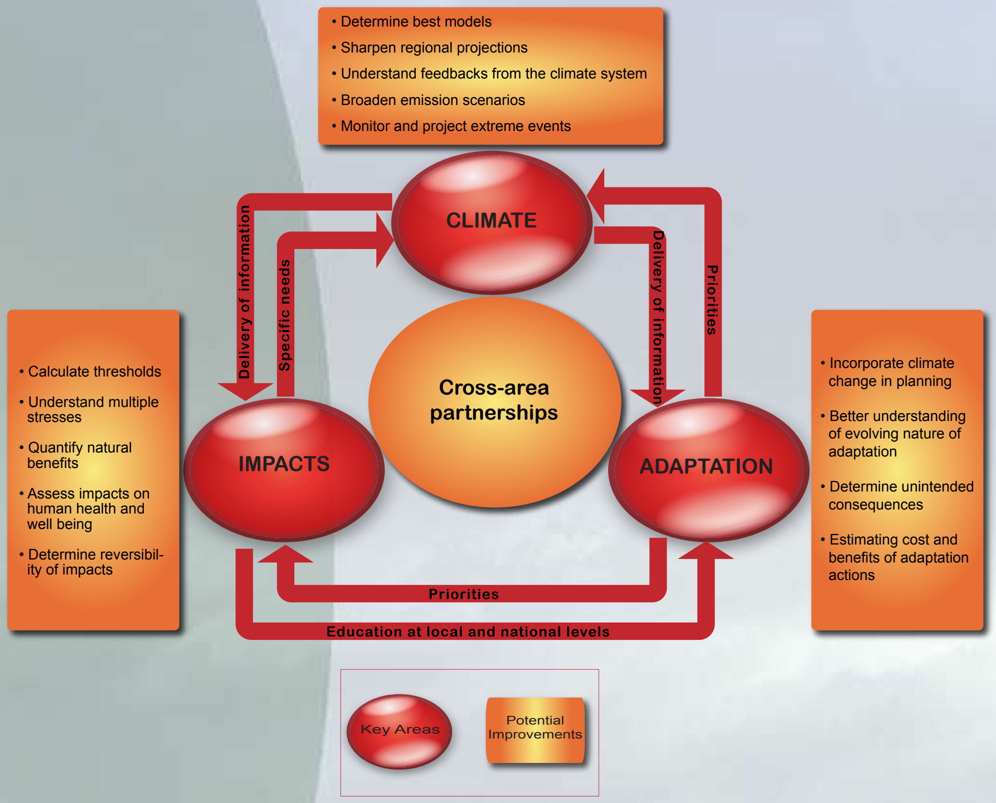
MetLife and Allstate report giving incentives to customers that install storm shutters and other measures to “wind-proof” their homes. A number of insurers, including Allstate and State Farm, have pushed for the adoption of improved, well-enforced building codes, which serve to both reduce insurance losses and reduce heat-trapping emissions, demonstrating synergies between mitigation and adaptation. A post-Katrina analysis revealed that per-capita economic losses were three-times lower in areas where building codes and comprehensive land-use planning were in use.

Examples of Adaptation Goals and Actions

Planning Area	Goal	Sample Actions
Water Supply	Expand and diversify water supply	- Connect regional water systems - Enhance existing groundwater supplies through aquifer storage and recovery - Develop advanced wastewater treatment capacity for water reuse ("gray water")
	Increase usable storage in reservoirs	- Add capacity to reservoirs by raising dam height - Adjust reservoir operations to reflect changing conditions
	Reduce demand/improve efficiency	- Increase billing rates for water - Change building codes to require low flow plumbing fixtures - Install high efficiency delivery systems for irrigated agriculture - Meter all water uses
	Increase ability to transfer water between users	- Use water banks, water pools, and water markets to facilitate the reallocation of water resources - Renegotiate transboundary water agreements where applicable
	Increase drought preparedness	- Update drought management plans to recognize changing conditions - Increase authority to implement water restrictions and other emergency measures as needed
Coasts	Reduce shoreline erosion	- Preserve ecological buffers to allow for inland beach migration - Enhance shoreline protection where retreat and accommodation are not possible
	Reduce property damage from erosion, flooding events, sea level rise	- Reduce development in coastal hazard areas - Incorporate climate change impacts into design requirements for coastal structures - Move or abandon shoreline infrastructure - Restore wetlands for run-off storage and flood control
	Maintain or enhance coastal habitat	- Preserve ecological buffers to allow for inland migration of wetlands, salt marshes, and other habitat systems - Reduce spread of invasive species
Agriculture	Adjust production to reflect changing conditions	- Change planting dates - Consider double cropping where longer growing seasons allow - Change planting varieties - Promote greater use of heat-resistant, insect-resistant and disease-resistant crops
	Improve agricultural water supply and use	- Promote new irrigation technologies to improve water use efficiency - Promote water conservation - Use market forces to distribute water - Diversify and expand water infrastructure
	Improve information used in managing agriculture	- Be aware of how climate change affects global agriculture - Work with county extension agents to distribute information to farmers on projected climate change impacts to agriculture

Pathways to Improved Decision Making

The focus of this report has been spread across the three interrelated areas of climate, impacts and adaptation illustrated in the figure below. Scientists and decision-makers must effectively work together to address the challenges and opportunities of our changing climate. Scientists must be able to accurately describe changing conditions in ways that are both scientifically meaningful and also relevant to decision makers, understand impacts, identify information needs, and develop strategies to help decision makers plan for adaptation to a changing climate and to reduce negative climate effects. This effort will help to effectively address problems of today, and improve our knowledge and planning for the future. It will help determine how we need to invest in research, evaluations, information services, and climate education. In the process of putting the report together, questions arose that highlighted shortcomings and limitations that should be addressed in each area. The following are the key questions along with answers that point toward pathways to improved decision making.



CLIMATE:
Analysis of past, current and future climate, the causes of climate change and the factors that can amplify or minimize it.

Assuring continued capability for documenting climate system evolution

Essential climate variables are not being adequately monitored. How can we do a better job of detecting changes in essential climate variables.
We must improve the observing systems that are necessary for providing high quality and comprehensive essential climate variables, both from surface-based observations and from satellites, so that we can accurately document the evolution of the global climate system. Without solid observation information it is very difficult to attribute known changes to any particular cause (e.g., by natural changes or by human-induced changes). Although significant investments are being made, there are substantial concerns about our ability to adhere to the United Nations' Framework Convention on Climate Change Global Climate Monitoring Principles to allow for unequivocal documentation of climate evolution. In addition this would require measuring changes in all the essential climate variables identified by the Climate Change Science Program strategic plan.

Determine best models

There are now well over a dozen climate models. What models are best for what purposes? Can more reliance be placed on some models?
All climate models are not created equal. Each has a variety of strengths and weaknesses. In this report we used all available models because there is currently no reliable way to identify which models are the best for North America. If the best models for U.S. projections were known so only the best were used, the projections in future evaluations would be sharpened. With standards and relevant observation information, the different models can be appropriately compared.

Improve regional projections

Climate change information particularly important for local and regional decision making. How can we provide local-scale climate change information to decision makers?

Today, global climate models are only able to make projections for large regions. There are not enough computer resources to provide information at the local level and, even if adequate computer resources existed, the models are not designed to take into account local-scale physical processes. Yet it is local information that is needed for communities to make informed decisions on how best to adapt to their local changing climate. This report adjusts projected large-scale information in order to make finer scale analyses. Another method is to use a regional model that uses the large-scale model projections as input. The downside to both of these methods is that some regionally important phenomena are not adequately taken into account. Hurricanes and El Niños, for example, are particularly difficult for large-scale global models to reproduce accurately. Decreasing the scale on which global climate models are run and incorporating appropriate smaller-scale physical processes in the models would require, among other things, faster computers, but would provide better local information to decision makers.

Understand how the climate system responds to change

Earth system feedbacks to global climate change are not generally modeled. What potentially important effects are they ignoring?

Scenarios for future emissions of greenhouse gases are used for climate models in this report. Yet there are many possible responses from the earth system that are not well quantified and therefore not taken into account in model projections. For example, studies show that substantial amount of the carbon safely stored for thousands of years in permafrost will likely be released as methane when the permafrost thaws. As methane is a greenhouse gas, more methane would cause additional warming. Also, melting ice and soot deposited on ice reduce surface reflection, which means that more energy is absorbed, thus increasing surface warming. Oceans absorb one third of global carbon emissions, but this effect is dependent upon changes in ocean temperature and circulation. Wildfires are responding to climate change. When a fire burns it releases gases and particles into the atmosphere and also changes how much sunlight is reflected off the surface, all of which also impacts climate. These responses are not yet fully understood but must taken into account in order to make more accurate climate projections.

Expand emission scenarios

Global carbon emissions now exceed the highest IPCC emission scenarios of future change. What can be done to better inform policy?

Recent global carbon dioxide emissions have actually been higher than the emissions that were projected for this time by the highest emission scenario used in this report. A wider range of scenarios is needed in order to take into account all plausible futures. For example, the scenarios we used do not adequately take into account the effect of rising crude oil costs into consideration of future emissions nor do they include changes in land cover associated with producing biofuels. Will higher fuel costs lead to a quicker adaptation of solar and wind power? Also, current emission scenarios do not adequately take into account potential agreements to limit greenhouse gas emissions. Without emission scenarios that include these possible futures and others, models can not adequately project future climate change. [1, 2]

Monitor and project extreme events

Extreme events have tremendous impacts, yet many kinds of events are not being accurately observed and adequately projected. How can this be addressed?

At the present time, we do not know the trends in tornadoes, severe local thunderstorms, or the frequency of hail because there have been so many changes in the observing methods used to detect and document them. Furthermore, climate models can not sufficiently reproduce all of the processes of the atmosphere that contribute to local severe weather. Therefore, this report does not discuss how local severe weather events, such as the number or intensity of tornadoes, are likely to change in the future. Hurricanes are another type of extreme event that is very important to the United States. Observations are better for hurricanes than for local severe events, but more information is still needed to fully understand how the number and intensity of hurricanes has changed over the years. Developing climate models that can make projections for areas five miles or less will improve understanding for both hurricanes and local severe weather, and allow scientists to evaluate the conditions that are favorable for these extreme events.

IMPACTS:
Identification of the past, present, and future impacts of climate change on society as well as managed and natural systems.

Calculate thresholds

Crossing certain thresholds can lead to dramatic effects. Are there other thresholds we should be watching for?
There are many different thresholds, but even where they are known, their potential impacts are not fully understood. For example, as carbon dioxide in the atmosphere increases, carbon dioxide in the ocean increases as well, making the ocean more acidic. There is evidence that, as the ocean becomes more acidic, it is harder for marine organisms to take calcium out of seawater to produce corals and shells. There is a threshold beyond which coral reefs can not survive but we are not sure yet when that point will be reached. The impacts from climate change will likely occur in bursts as thresholds are crossed. These bursts will occur in response both to biological changes and physical changes, such as melting ice. In general, more research is needed to quantify the impacts of crossing particular thresholds.

Understand multiple stresses

Multiple stresses are common in society and the environment. And so we need to be prepared to deal with multiple stresses. Is climate change likely to produce other complex stresses that we should know about?
Climate change is occurring in the context of other changes including changes in the chemistry of the atmosphere and precipitation, and changes in land cover and land use. We need to better understand how these stresses interact with climate change to affect ecological and social systems. Research in this area should include multi-factor experiments and simulation modeling.

Quantify natural benefits

Nature provides us with many benefits such as food, fuel and fiber as well as many services we take for granted such as the cleansing of air and water. Are there benefits that we depend upon that are in jeopardy?
More research is needed to adequately quantify vulnerable resources. There are likely to be both gradual changes in climate averages and changes in the occurrence of extreme weather and climate events such as severe storms, droughts, floods, and fires as we move from the present climate into the future climate. These changes will likely impact the natural benefits in ways we do not yet fully understand.

Assess impacts on human health and well being

Climate change is going to impact many aspects of human health and well being. Are these impacts being adequately measured and projected so we can take action before a problem gets too serious?
In some cases, yes. For example, the United States has an excellent disease reporting system that accurately monitors the spread of diseases such as the West Nile virus. In other cases the answer is no. For example, some projections of the potential areas of malaria infection in the United States failed to adequately take into account the ability to control the mosquitoes that carry malaria should an outbreak start. Presently, the spread of diseases and human illnesses caused by weather and climate are not accurately monitored and classified according to weather phenomenon. Predicting future costs of human health impacts and well-being is difficult without accurate information from the past. Most diseases are of biological origin and have climate thresholds which are difficult to predict but may affect the distribution of diseases. In addition, the combined impacts of global and local climate effects must also be considered. For instance, ozone pollution, which occurs at the local level, and heat spells, which may occur due to regional or global changes in climate, can both be harmful to human health.

Determine reversibility of impacts

Some aspects of climate change appear to be irreversible . Are the irreversible impacts being monitored adequately so that we can take precautions?
To better identify our vulnerability will require long-term information that is both location specific and species specific. For example, some plant and animal species adapted to the cold tops of mountains will be displaced by species from lower elevations as warming allows those species to move up slope. Land managers who are informed by continuous, long-term observations may be able to preserve pockets of selected environments.

ADAPTATION:
Planning decisions from individual to national levels that take climate change as well as values such as quality of life into consideration.

Incorporate climate change in planning

We didn't pay much attention to climate change in the past and our country developed just fine. Why do we need to pay so much attention to it now?
Climate variability has had profound impacts on the United States in the past. A good example is the intensive farming in the short grass prairies of the Plains states in the early 1900s. This farming came to a dramatic halt as the droughts of the Dust Bowl started in 1930, causing dark clouds of topsoil to blow eastward. By 1940, 2.5 million people had moved out of the region. This tragedy could have prevented if there was better farm land practices and a better understanding of the risk of prolonged drought in the plains. We are now faced with climate change which will impact all regions of the country. If climate change is not taken into account in almost all aspects of planning, we will miss opportunities to minimize risk or maximize benefits from climate change. It will be important for climate and planning experts to work with those who make policy decisions in order to fully incorporate climate change information into planning.

Better understanding of evolving nature of adaptation

Climate is no longer constant. It will now continuously evolve so adaptation must also be dynamic. How can this adaptation be most effective?
In the past, some reports have discussed planning for the future as if we are moving directly from Climate A to Climate B and it was the transition between the two climates that we needed to focus on. This report has tried to stress that the climate, looking back over the last few decades and looking forward to the end of the Century and beyond, will be in a continual state of transition. The climate will be constantly changing and therefore our adaptation requirements will be constantly changing. It is important to understand vulnerabilities and adaptive abilities, and to support development of best practices for adaptation. Continual communication and exchange of information among climate scientists, researchers of climate impacts, decision makers, and the public is necessary. Better communication between these groups will help communities and individuals make the best decisions to adapt to their changing climate.

Determine unintended consequences

We've seen food prices sky rocket around the world while more corn is being turned into fuel forcing corn grown for food on to more marginal land. This consequence was not widely discussed when ethanol policy was being debated. Are there other unintended consequences awaiting us?
It is possible that if we focus on one issue associated with climate change we might inadvertently create another problem. Other unintended consequences will arise as both humans and natural systems respond to climate change. Because the cause of global warming, fossil fuel use, is such a large part of the world's economy and politics, any effort to address it will be bound to have multiple effects. Furthermore, because global warming's direct effects will be impacting societies in all parts of the world, unanticipated impacts are bound to arise and may be far reaching. As illustration, drought in one country may lead to increased immigration into another. More research is needed to determine and quantify the unintended consequences in time to proactively respond to them.

Estimating costs and benefits of adaptation actions

This Unified Synthesis Product outlines a number of adaptation strategies to help society cope with climate change in the context of other stresses. Do we have adequate methods to carry out cost-benefit analyses for such adaptation strategies?
Cost-benefit analysis remains a major challenge when dealing with adaptations to climate change. A complete analysis often requires valuing market and non-market goods and services, and we do not yet know how to do this. A particularly difficult issue is determining the value of irreversible changes. These costs could be factored into a more quantitative and complete analysis of climate change by considering earth system chemistry and physics along with the structure and function of land and water ecosystems. This would enable us to more wisely choose among adaptation choices.

David M. Anderson

Dr. David M. Anderson is the Director for the World Data Center for Paleoclimatology, Chief of the Paleoclimatology Branch of NOAA's National Climatic Data Center, and an Associate Professor Adjoint at the University of Colorado. As a paleoclimatologist, his research interests lie in the marine geologic record of the Asian monsoons and other aspects of tropical air-sea interaction, and in the ocean's role in regulating atmospheric carbon dioxide in the past and future. He has served on national and international advisory committees for paleoclimate research, ocean research, and data management issues, and contributed to national reports on abrupt climate change and climate extremes. Dr. Anderson received a B.S. degree in Biology in 1981, an M.S. in Marine Science from San Jose State University, and an M.S. and Ph.D. in Geological Sciences from Brown University in 1991.

Donald F. Boesch

Dr. Donald F. Boesch has served as a Professor in and President of the University of Maryland Center for Environmental Science since 1990. He currently is also Vice Chancellor for Environmental Sustainability for the University System of Maryland. He earned a B.S. in Biology from Tulane University and a Ph.D. in Biological Oceanography from the College of William and Mary. Dr. Boesch has conducted research on coastal and continental shelf environments along the Atlantic Coast and in the Gulf of Mexico, eastern Australia and the East China Sea, focusing on benthic ecology, sedimentary processes, tidal wetlands, and eutrophication. He has long been active in extending knowledge of environmental and resource management at regional, national and international levels, particularly with regard to the restoration of large ecosystems including the Chesapeake Bay, Mississippi Delta, Florida Everglades and Baltic Sea. Dr. Boesch has served multiple terms on the Ocean Studies Board of the National Research Council and has chaired NRC committees on marine environmental monitoring, coastal ecosystem science, and adaptive management of water resources projects. He was co-chair of the coastal and marine sector team for the First U.S. National Assessment of the Potential Consequences of Climate Variability and Change and chairs the Scientific and Technical Working Group of the Maryland Commission on Climate Change.

Virginia Rose Burkett

Dr. Virginia Rose Burkett is the Chief Scientist for Global Change Research at the U.S. Geological Survey. She was formerly Chief of the Forest Ecology Branch at the National Wetlands Research Center. Dr. Burkett has served as Director of the Louisiana Department of Wildlife and Fisheries, Director of the Louisiana Coastal Zone Management Program, and Assistant Director of the Louisiana Geological Survey. She has published extensively on the topics of global change and low-lying coastal zones. She was a Lead Author on the United Nations Intergovernmental Panel on Climate Change (IPCC) Third and Fourth Assessment Reports (2001 and 2007) and the IPCC Technical Paper on Water (2008). She coordinated both the Coastal and Southeast synthesis chapters of the U.S. National Assessment of climate change and its impacts (2001). Burkett has been appointed to over 40 Commissions, Committees, Science Panels and Boards during her career. She received a B.S. in zoology and an M.S. in botany from Northwestern State University of Louisiana; her doctoral work in forestry was completed at Stephen F. Austin State University in 1996.

Lynne M. Carter

Dr. Lynne M. Carter is the Director of the Adaptation Network, a non-profit (501 c3) organization, and a project of the Earth Island Institute. Dr Carter has been working on climate change issues since her first workshop in 1989 as the executive director of the Center for Ocean Management Studies at the University of Rhode Island. She became the Regional Liaison to all of the 19 regions for the U.S. National Assessment of the Potential Consequences of Climate Variability and Change in 1998. She has developed and taught semester-long and short courses on climate change issues (including the first climate change course in the U.S. to combine science, society, and policy in 1991), both for formal education (students and faculty) and informally for the interested public and for informal educators (e.g. museums, nature centers, etc). She developed a climate change distance-learning course that was offered through the University of Maryland, has taught adult students at Vermont College, and was an invited teaching fellow at the Environmental Change Institute at Oxford University. She has delivered many public presentations around climate change issues. Dr. Carter has organized conferences and workshops on various aspects of climate change, including for the bi-national New England Governors and Eastern Canadian Premiers on likely climate impacts to natural resources. She has written and contributed to articles and reports on climate change for a variety of audiences. Dr. Carter holds a B.S. in biology from the University of Hartford, an M.S. in zoology from the University of Connecticut, a Master of Marine Affairs from the University of Rhode Island, and a Ph.D. in Maritime Studies (climate change focus) from the University of Wales, Cardiff.

Stewart J. Cohen

Dr. Stewart Cohen is senior researcher with the Adaptation and Impacts Research Division of Environment Canada, and an Adjunct Professor with the Department of Forest Resources Management of the University of British Columbia (UBC). Dr. Cohen's research interests are in climate change impacts and adaptation at the regional scale, and exploring how climate change can affect sustainable development. Recent work includes a case study on climate change and water management in the Okanagan region of British Columbia, and a study on climate change visualization led by Stephen Sheppard of UBC. He is currently a member of the advisory committee for the Columbia Basin Trust climate change adaptation program. Previously, he led the Mackenzie Basin Impact Study (MBIS), a 7-year effort focused on climate change impacts in the western Canadian Arctic, completed in 1997. His earlier work included research on impacts in the Great Lakes and Saskatchewan River Basins. He has been a Lead Author for the Intergovernmental Panel on Climate Change (IPCC) Third and Fourth Assessment Reports, and has contributed to other IPCC documents and technical workshops since 1992. Dr. Cohen is a geographer having received his B.Sc., M.Sc. and Ph.D. from McGill University, University of Alberta, and University of Illinois, respectively.

Nancy B. Grimm

Dr. Nancy B. Grimm is a Professor of Life Sciences and Leader of the Ecology, Evolution, and Environment Science faculty at Arizona State University (ASU). Her M.S. (1980) and Ph.D. (1985) degrees are from ASU, where she has held research scientist and faculty positions since 1990. An ecosystem ecologist and biogeochemist, Dr. Grimm studies how landscape heterogeneity and climate variability influence retention, cycling, and transport of nitrogen, both in desert and urban landscapes. She is Lead Principal Investigator and Co-Director of the Central Arizona-Phoenix Long-Term Ecological Research (LTER) project, a study of the Phoenix metropolis and surroundings that is one of the first comprehensive investigations of an urban ecosystem. In that capacity, Dr. Grimm oversees and coordinates interdisciplinary research in urban ecology involving over 100 scientists in many fields. She is a believer in interdisciplinary approaches to answering fundamental ecological questions, collaborating with hydrologists, engineers, geologists, chemists, sociologists, geographers, climatologists, and anthropologists in her urban and stream studies. She is a past president of the Ecological Society of America and the North American Benthological Society, and has served on numerous editorial boards and advisory or review panels. Dr. Grimm has published over 110 research articles and book chapters with students and colleagues, and has received over $25 million in collaborative research and training awards, mostly from the National Science Foundation.

Susan Joy Hassol

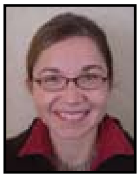
Susan Joy Hassol is Director of Climate Communication. She is an analyst and author known for her ability to translate science into English, making complex issues accessible to policymakers and the public for two decades. She authored *Impacts of A Warming Arctic*, the synthesis report of the Arctic Climate Impact Assessment, and testified about the impacts of Arctic warming before the U.S. Senate. Ms. Hassol wrote HBO's documentary, *Too Hot Not To Handle*. She was a lead author of *Climate Change Impacts on the United States*, the synthesis report of the U.S. National Assessment of the Consequences of Climate Change. She contributed a chapter on Arctic climate impacts to a book titled *Avoiding Dangerous Climate Change*. She was Senior Editor of the U.S. Climate

Change Science Program's (CCSP) report *Weather and Climate Extremes in a Changing Climate* and Associate Editor of the CCSP report *Temperature Trends in the Lower Atmosphere*. In 2006, Ms. Hassol was honored by the Climate Institute with its first ever award for excellence in climate science communication. More information can be found at climatecommunication.org.

Jerry L. Hatfield

Dr. Jerry L. Hatfield is the Laboratory Director of the USDA-ARS National Soil Tilth Laboratory in Ames, Iowa, a position he has held since 1989. His expertise is in the quantifications of spatial and temporal interactions across the soil-plant-atmosphere continuum and his personal research has focused on the interactions of water, light, carbon, and nitrogen in cropping systems. Part of this effort involves the interactions with the measurement sites in Iowa as part of the Midcontinent Intensive Experiment as part of the North American Carbon program. He serves as the Lead Author for the Agricultural section of the Climate Change Science Program's (CCSP) Synthesis and Assessment Product (SAP) 4.3 "The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity" and an author of "Emissions from Livestock and Manure Management" for the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for National Greenhouse Gas Inventories. He is the author of numerous publications that address environmental quality and agriculture, quantification of plant stress to water and temperature, remote sensing of agricultural systems, and energy and carbon exchanges across agricultural landscapes. He is the Past-President of the American Society of Agronomy and member of the Board of Directors of the Soil and Water Conservation Society. He serves as the USDA-ARS representative to the Heinz Center project on the State of the Nation's Ecosystems, the Key Indicators Initiative, National Audubon society project on Waterbirds on Working Lands, and Agricultural Air Quality Task Force for USDA.

Katharine Hayhoe



Katharine Hayhoe is a Research Associate Professor in the Department of Geosciences at Texas Tech University and Principal Scientist and CEO of ATMOS Research & Consulting. She holds a B.Sc. in Physics from the University of Toronto (1994) and an M.S. in Atmospheric Sciences from the University of Illinois (1997). Her research examines the potential impacts of human activities on the global environment, using numerical model simulations of the earth-atmosphere system for both global and regional climate as well as chemical transport and integrated assessment modeling. To that end, Ms. Hayhoe has served as lead author for a number of regional assessments examining climate impacts on and adaptation potential for energy and water supply, agricultural and natural ecosystems, and infrastructure and public health. Assessments include the Great Lakes region (2003), the State of California (2004, 2006, 2008), the U.S. Northeast (2006, 2007), and the City of Chicago (2008). Together with these assessments, her more than 40 peer-reviewed studies, published in journals including *Science*, *Proceedings of the National Academy of Sciences*, and *Climatic Change*, have resulted in her work being presented before the U.S. Congress, cited by the IPCC Fourth Assessment Report, and highlighted by state and federal agencies as motivation for the development and implementation of policies to reduce emissions from human activities. Her work has also been featured in over 200 newspapers and media outlets around the world, including National Public Radio, the British Broadcasting Corporation, Discovery Channel, National Geographic, and Sports Illustrated.

Anthony Janetos

Dr. Anthony C. Janetos is the Director of the Joint Global Change Research Institute, a joint venture between the Pacific Northwest National Laboratory and the University of Maryland. Previously, he served as Vice President and Director of the Global Change Program at the H. John Heinz III Center for Science, Economics and the Environment; Vice President for Science and Research at the World Resources Institute; and Senior Scientist for the Land-Cover and Land-Use Change Program in NASA's Office of Earth Science. He also was Program Scientist for NASA's Landsat 7 mission. Dr. Janetos has many years of experience in managing scientific and policy research programs on a variety of ecological and environmental topics, including air pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. Dr. Janetos has served on numerous National Research Council (NRC) committees, including the Decadal Survey for Earth Observations. He is a member of the NRC's standing Climate Research Committee and a Fellow of the American Association for the Advancement of Science. He was also a co-chair of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change and an author of the IPCC Special Report on Land-Use Change and Forestry and the Global Biodiversity

Assessment, and the Millennium Ecosystem Assessment. Most recently he was a co-convening lead author of the Climate Change Science Program's (CCSP) Synthesis and Assessment Product (SAP) 4.3, Climate Change Impacts on US Ecosystems. With many collaborators, Dr. Janetos has written and spoken about the need to understand the scientific, environmental, economic, and policy linkages among the major global environmental issues, and the need to keep basic human needs in the forefront of the thinking of the environmental science and policy communities. Dr. Janetos graduated Magna cum Laude from Harvard College with a bachelor's degree in biology and earned a master's degree and a Ph.D. in biology from Princeton University.

Thomas R. Karl

Dr. Thomas R. Karl is the Director of NOAA's National Climatic Data Center and is NOAA's Program Manager for Climate Observations and Analysis. Dr. Karl is author of many climatic atlases and technical reports, and has published over 150 articles in various scientific journals. He was identified as one of the most frequently cited Earth Scientists of the 1990s. Dr. Karl has been a Lead Author on several Intergovernmental Panel on Climate Change (IPCC) Assessments and most recently has served as a Review Editor. He was part of the IPCC organization that received the 2007 Nobel Peace Prize. Dr. Karl is a fellow of the American Meteorological Society and the American Geophysical Union, and a National Associate of the National Research Council. In 2002, he was elected to serve on the Council of the American Meteorological Society and has recently been elected to serve a term as President of the Society.

Jack A. Kaye

Dr. Jack A. Kaye currently serves as Associate Director for Research of the Earth Science Division within NASA's Science Mission Directorate. He has been a member of the Senior Executive Service since August, 1999, managing NASA's Earth Science Research Program. Earlier positions in his nearly 24 year career at NASA include being a Space Scientist at the Goddard Space Flight Center and Manager of the Atmospheric Chemistry Modeling and Analysis Program at NASA headquarters. His academic training is in chemistry (B.S. Adelphi University, 1976; Ph.D., California Institute of Technology, 1982). As Associate Director for Research, Dr. Kaye is responsible for the research and data analysis programs for Earth System Science, covering the broad spectrum of scientific disciplines that constitute it. He represents NASA in many interagency and international activities and has been an active participant in the U.S. Climate Change Science Program (CCSP) in which he currently serves as NASA principal and Vice Chair of the Subcommittee on Global Change Research, as well as NASA's representative to the Senior Users' Advisory Group for the National Polar Orbiting Operational Environmental Satellite System and to the Joint Subcommittee on Ocean Science and Technology. He is a member of the Steering Committee for the Global Climate Observing System. He has received numerous NASA awards, as well as been recognized as a Meritorious Executive in the Senior Executive Service in 2004. He has published more than 50 refereed papers, contributed to numerous reports, books, and encyclopedias, and edited the book *Isotope Effects in Gas-Phase Chemistry* for the American Chemical Society.

Jay Lawrimore

Jay Lawrimore is Chief of the Climate Monitoring Branch at NOAA's National Climatic Data Center (NCDC). Since 2000 he has led a team of scientists that monitors the Earth's climate on an operational basis to provide policymakers, business leaders, scientists, and the media with historical and current perspectives on the state of the national and global climate. As the pace of climate change has accelerated, the capacity to monitor the climate on an ongoing basis has grown in importance. This program culminates each year with a Bulletin of the American Meteorological Society report produced through a partnership with 150 scientists from more than 30 countries. Beyond State of the Climate reporting, Mr. Lawrimore leads other programs that span a range of issues at the center of the nation's need for climate information. He was instrumental in establishing the North American Drought Monitor through a trilateral partnership between the United States, Mexico, and Canada to enhance drought monitoring on the North American continent.

James J. McCarthy

Dr. James J. McCarthy is Alexander Agassiz Professor of Biological Oceanography and from 1982 until 2002 he was the Director of Harvard University's Museum of Comparative Zoology. He is the Head Tutor for Harvard's undergraduate degree program in Environmental Science and Public Policy, and the Master of Harvard's Pforzheimer House. He received his undergraduate degree in biology from Gonzaga University, and his Ph.D. from Scripps Institution of Oceanography. His research interests relate to the regulation of plankton productivity in the sea, and in recent years have focused on regions that are strongly affected by seasonal and inter-annual variation in climate. From 1986 to 1993, he served as the first chair of the Scientific Committee for the International Geosphere - Biosphere Program. From 1986 to 1989 he was the founding editor for the American Geophysical Union's Global Biogeochemical Cycles. For the Third Intergovernmental Panel on Climate Change (IPCC) Assessment (2001), he headed Working Group II, which had responsibilities for assessing impacts of and vulnerabilities to global climate change. He was also one of the lead authors on the 2005 Arctic Climate Impact Assessment, and a Vice-Chair of the 2007 Northeast Climate Impacts Assessment. He has been elected a Fellow of the American Association for the Advancement of Science, a Fellow of the American Academy of Arts and Sciences, and a Foreign Member of the Royal Swedish Academy of Sciences. Currently, he is President of the American Association for the Advancement of Science.

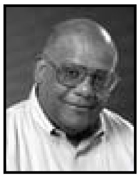
David McGuire

Dr. A. David McGuire is a Professor of Ecology in the U.S. Geological Survey's Alaska Cooperative Fish and Wildlife Research Unit located at the University of Alaska Fairbanks (UAF). He is also director of the Spatial Ecology Laboratory in the Institute of Arctic Biology at UAF. He earned his B.S. and M. Engineering in Electrical Engineering from Cornell University in 1976 and 1977, and his M.S. and Ph.D. in Biology from UAF in 1983 and 1989. Dr. McGuire has conducted studies on how responses of terrestrial ecosystems to climate change may influence the climate system since 1990. He served two terms on the Board of Editors for Ecological Applications and served on the Polar Research Board's committee to review NASA's Polar Geophysical Data Sets. Dr. McGuire is serving on several national level science steering committees (SSCs) including the Carbon Cycle Science Steering Group of the U.S. Climate Research Program, the SSC for the Study of Environmental Arctic Change (SEARCH), and the SSC for the Arctic Community-wide Hydrological Analysis and Monitoring Program. He has also served on several international committees concerned with global change science in northern high latitudes. Dr. McGuire is currently serving as co-chair of the U.S. Arctic Research Commission study to develop the report "Scaling Studies in Arctic System Science and Policy Support: A Call-to-Research" and as chair of Arctic Monitoring and Assessment's Program's scientific assessment of the arctic carbon cycle.

Jerry M. Melillo

Dr. Jerry M. Melillo is the Director of The Ecosystems Center at the Marine Biological Laboratory in Woods Hole, Massachusetts, and a Professor of Biology at Brown University. His center at Woods Hole focuses on environmental research in three areas: global change; management of coastal zone ecosystems; and globalization and transformation of the tropical landscape. Dr. Melillo specializes in understanding the impacts of human activities on the biogeochemistry of ecological systems, using a combination of field studies and simulation modeling. In 1996 and 1997, he served as the Associate Director for Environment in the U.S. President's Office of Science and Technology Policy. Dr. Melillo just completed terms as the President of the Ecological Society of America and of the Scientific Committee on Problems of the Environment (SCOPE), the environmental assessment body of the International Council for Science. He is an honorary Professor in the Institute of Geophysical Sciences and Natural Resources Research, Chinese Academy of Sciences, a member of the American Philosophical Society, and a Fellow of the American Academy of Arts and Sciences. His publication record includes more than 200 peer-reviewed articles, two ecology textbooks and three edited volumes on biogeochemistry.

Edward L. Miles



Dr. Edward L. Miles is the Virginia and Prentice Bloedel Professor of Marine Studies and Public Affairs at the University of Washington. He holds joint appointments in the School of Maine Affairs of the College of Ocean and Fisheries Sciences and the Evans School of Public Affairs. He is also a Senior Fellow in the Joint Institute for the Study of the Atmosphere and Ocean (JISAO), where he serves as the Co-Director of the

Center for Science in the Earth System and leader of the Climate Impacts Group. Dr. Miles has been a participant in the work of the Intergovernmental Panel on Climate Change (IPCC) since February 1994. On April 29, 2003 he was elected to membership in the U.S. National Academy of Sciences and on October 14, 2005 he was elected to the rank of Fellow of the American Association for the Advancement of Science (AAAS). Dr. Miles's fields of specialization are international science and technology policy, marine policy and ocean management, and the impacts of climate variability and change at global and regional scales.

Evan Mills

Dr. Evan Mills has worked on energy and environmental systems analyst since the early 1980s, from local to global scales. He received his Masters of Science degree from the Energy and Resources Group at UC Berkeley in 1987 and his Ph.D. from the Department of Environmental and Energy Systems Studies at the University of Lund in Sweden in 1991. Dr. Mills is currently a Staff Scientist at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (LBNL), one of the world's leading research centers on energy and environment with a staff of approximately 400 people, and past leader of LBNL's Center for Building Science. His work spans the domains of energy management, risk management, and climate change impacts, with emphasis on the nexus between these as illustrated in the case of innovations emerging from the insurance industry. He has published over 200 technical articles and reports and has contributed to nine books. He is a member of the Intergovernmental Panel on Climate Change (IPCC), an organization which shared the 2007 Nobel Peace Prize with former U.S. Vice President Albert Gore.

Jonathan Overpeck

Dr. Jonathan Overpeck is a climate system scientist at the University of Arizona, where he is also the Director of the Institute for the Study of Planet Earth, as well as a Professor of Geosciences and a Professor of Atmospheric Sciences. He received his B.A. from Hamilton College, followed by a M.Sc. and Ph.D. from Brown University. Dr. Overpeck has published over 120 papers in climate and the environmental sciences, and recently served as a Coordinating Lead Author for the Nobel prize winning United Nations Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (2007). He has also been awarded the U.S. Department of Commerce Bronze and Gold Medals, as well as the Walter Orr Roberts award of the American Meteorological Society, for his interdisciplinary research. Dr. Overpeck has also been a Guggenheim Fellow, and was the 2005 American Geophysical Union Bjerknes Lecturer. He serves on the Board of Reviewing Editors for *Science* Magazine.

Jonathan Patz

Jonathan Patz, MD, MPH, is a Professor & Director of Global Environmental Health at the University of Wisconsin in Madison. He Co-chaired the health expert panel of the U.S. National Assessment on Climate Change and was a Convening Lead Author for the United Nations/World Bank Millennium Ecosystem Assessment. For the past 14 years, Dr. Patz has been a lead author for the United Nations Intergovernmental Panel on Climate Change (IPCC), an organization awarded the 2007 Nobel Peace Prize. He is President of the International Association for Ecology and Health and has written over 75 peer-reviewed papers and a textbook addressing the health effects of global environmental change. He has served on several scientific committees of the National Academy of Sciences, and currently serves on science advisory boards for both the Centers for Disease Control and Prevention (CDC) and the Environmental Protection Agency (EPA). Dr. Patz received an Aldo Leopold Leadership Fellows Award in 2005, and shared the Zayed International Prize for the Environment in 2006. He has earned medical board certification in both Occupational/Environmental Medicine and Family Medicine and received his medical degree from Case Western Reserve University (1987) and his Master of Public Health degree (1992) from Johns Hopkins University.

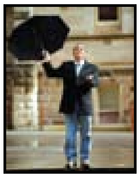
Thomas C. Peterson

Dr. Thomas C. Peterson is a physical scientist at NOAA's National Climatic Data Center in Asheville, North Carolina. After earning his Ph.D. in Atmospheric Science from Colorado State University in 1991, Dr. Peterson primarily engaged in creating NCDC's global land surface data set used to quantify long-term global climate change. Key areas of his expertise include data archaeology, quality control, homogeneity testing, international data exchange and global climate analysis using both *in situ* and satellite data. He was a lead author on the Fourth Assessment Report of the Nobel Prize winning Intergovernmental Panel on Climate Change's Fourth Assessment Report. Currently he is a member of the Global Climate Observing System Atmospheric Observation Panel for Climate and chairs the United Nations' World Meteorological Organization Commission for Climatology Open Programme Area Group on Monitoring and Analysis of Climate Variability and Change. The U.S. Department of Commerce has honored him with three Bronze Medal Awards and one Gold Medal Award. Essential Science Indicators ranked him as one of the top one percent of scientists in the field of Geosciences based on Journal Citation Reports. He is the author or co-author of over 60 peer-reviewed publications and three data sets.

Roger S. Pulwarty

Dr. Roger S. Pulwarty is a Physical Scientist and the Director of the National Integrated Drought Information System (NIDIS) Program at the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado. His interests and publications are on climate, assessing social and environmental vulnerability, and developing climate information services for risk management. Dr. Pulwarty's work focuses on the U.S. West, Latin America, and the Caribbean. From 1998 to 2002 he directed the NOAA/Regional Integrated Sciences and Assessments (RISA) Program. He leads the vulnerability and capacity assessments component of the World Bank-funded project on Mainstreaming Adaptation to Climate Change in the Caribbean. He is also a lead author on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report Working Group 2, the forthcoming IPCC Technical Report on Climate and Water Resources, and on the U.S. Climate Change Science Program Synthesis and Assessments Reports. He has testified before the U.S. Congress on climate, impacts and adaptation and is the NOAA liaison to the Western States Water Council.

Benjamin Santer



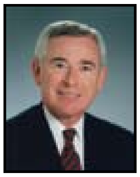
Dr. Benjamin Santer is an atmospheric scientist at Lawrence Livermore National Laboratory (LLNL). His research focuses on such topics as climate model evaluation, the use of statistical methods in climate science, and identification of natural and anthropogenic "fingerprints" in observed climate records. Dr. Santer's early research on the climatic effects of combined changes in greenhouse gases (GHGs) and sulfate aerosols contributed to the historic "discernible human influence" conclusion of the 1995 Report by the Intergovernmental Panel on Climate Change (IPCC). He spent much of the last decade addressing the contentious issue of whether model-simulated changes in tropospheric temperature are in accord with satellite-based temperature measurements. His recent work has attempted to identify anthropogenic fingerprints in a number of different climate variables, such as tropopause height, atmospheric water vapor, the temperature of the stratosphere and troposphere, and ocean surface temperatures in hurricane formation regions. Dr. Santer holds a Ph.D. in Climatology from the University of East Anglia, England, where he studied under Professor Tom Wigley. After completion of his Ph.D. in 1987, he spent five years at the Max Planck Institute for Meteorology in Germany, and worked with Professor Klaus Hasselmann on the development and application of climate fingerprinting methods. In 1992, Dr. Santer joined Professor Larry Gates at Lawrence Livermore National Laboratory's Program for Climate Model Diagnosis and Intercomparison. Dr. Santer served as convening lead author of the climate change detection and attribution chapter of the 1995 IPCC report. More recently, he was the convening lead author of a key chapter of the U.S. Climate Change Science Program's report on "Temperature Trends in the Lower Atmosphere".

Michael Savonis

Michael J. Savonis has 25 years of experience in transportation policy, with extensive expertise in air quality and emerging environmental issues. He has served as Air Quality Team Leader at the Federal Highway Administration (FHWA), since 1996. For the past 16 years, Mr. Savonis has overseen the Congestion Mitigation and Air Quality Improvement Program which invests more than $1.5 billion annually to improve air quality. He directs FHWA's transportation/air quality policy development, research program, and public education. He received the Department of Transportation's (DOT) Silver Medal in 1997 and FHWA's Superior Achievement Award in 2004. Mr. Savonis was instrumental to the creation of the DOT Center for Climate Change. He is co-Chair of the Transportation Research Board's Climate Change Subcommittee, was a member of the Air Quality Committee 1999 to 2004, and served as Chair of the Subcommittee on Transportation Control Measures, 2000 to 2004. He is author of several papers on climate and air quality, including: *The Gulf Coast*

Study, Synthesis and Assessment Product 4.7, Climate Change Science Program; *Toward a Strategic Plan for Transportation Air Quality Research, 2000-2010*, Transportation Research Record; and *Clean Air Through Transportation: Challenges in Meeting the National Ambient Air Quality Standards*, Report to Congress. Mr. Savonis holds a Masters Degree in Regional Planning from Cornell University and a B.S. in Chemistry from the State University of New York at Buffalo.

Gerry Schwartz



Dr. Henry G. "Gerry" Schwartz Jr., (Princeton University, Washington University in St. Louis, B.S. and M.S.; and California Institute of Technology, Ph.D.) is an internationally recognized leader in environmental and civil engineering. He spent virtually his entire career designing and managing major water, wastewater, and transportation projects throughout the country, serving as President/Chairman of Sverdrup/Jacobs Civil, one of the nation's most respected civil engineering firms, from 1993 until his retirement in 2003. Thereafter, he was a Senior Professor at Washington University until 2007. Earlier in his career, he served as President of the Water Environment Federation and was the founding Chairman of the Water Environment Research Foundation which now provides well over $10 million annually in water quality research funds. In 2001/2002 he was elected President of the American Society of Civil Engineers (ASCE) and created their Critical Infrastructure Response Initiative to address the nation's infrastructure security needs following the events of September 11, 2001. Recipient of many awards, Dr. Schwartz was inducted into the National Academy of Engineering in 1997 and received the Distinguished Alumni Award from California Institute of Technology in 2004. Today, he serves on the Board of Berger Group Holdings, Inc., is a member of the Executive Committee of the Transportation Research Board, and is a private consultant. He also chaired the National Research Council Committee that authored *Special Report 290: Potential Impacts of Climate Change on U. S. Transportation* published in 2008.

Eileen L. Shea

Eileen L. Shea has served as Director of the NOAA Integrated Data and Environmental Applications (NOAA IDEA) Center since fall of 2005. The NOAA IDEA Center was established to advance NOAA's mission objectives and meet critical needs for ocean, climate and ecosystem information to protect lives and property, support economic development and enhance the resilience of Pacific Island communities in the face of changing environmental conditions. On January 3, 2008, Ms. Shea assumed responsibility as the Chief of the Climate Services Division of the NOAA's National Climatic Data Center with responsibility for NCDC's programs in data access; data integration and visualization; user engagement, education and outreach; and international, national and regional climate services partnerships. Ms. Shea is involved in a number of Pacific Island regional endeavors in the field of environmental science and services including: membership on the Steering Committees for the Pacific Islands Global Climate Observing System (PI-GCOS) and Pacific Islands Global Ocean Observing System (PI-GOOS) programs; supporting the emergence of a Pacific Islands Integrated Ocean Observing System (PacIOOS) program; leading regional efforts to implement the Pacific Climate Information System (PaCIS) including serving as the first chair of the PaCIS Steering Committee, and in addition, Ms. Shea is Chair of the Pacific Risk Management 'Ohana (PRiMO). In early 2007 Ms Shea was elected to the rank of Fellow of the American Meteorological Society. Her educational experience focused on marine science and environmental law and resource management at the University of Delaware and the Virginia Institute of Marine Science, College of William and Mary.

John M.R. Stone

Dr. John M.R. Stone is an Adjunct Research Professor in the Department of Geography and Environmental Studies at Carleton University. Dr. Stone received a Ph.D. in Chemical Spectroscopy (1969) and an Honours B.Sc. in Chemistry (1966) from the University of Reading U.K. He held Post-Doctoral Fellowships, with the National Research Council of Canada and the Czechoslovak Academy of Sciences. Prior to his retirement from the federal government he served as Executive Director (Climate Change), for the Meteorological Service of Canada, Environment Canada; Director-General, Climate and Atmospheric Research, Environment Canada; Director (Meteorological Research Branch and Climate Research Branch), Atmospheric Environment Service, Environment Canada; and Co-ordinator for the Second World Climate Conference (on secondment from the Department of External Affair and International Trade). His experiences since 2005 include: Senior Fellow with the International Development Research Council; Senior Consultant, Gartner-Lee Consultants Ltd.; author of an assessment of Extreme Climate and Weather Events for the U.S. Climate Change Science Program and for an assessment on Agricultural Science and Technology for Development for the World Bank as well as giving talks on climate change to government and private sector audiences. His current and past professional responsibilities include: Member of the Bureau of the Intergovernmental Panel on Climate Change (IPCC), specifically as Vice-chair of Working Group I for Third Assessment Report and Vice-chair of Working Group II for Fourth Assessment Report; Chairman of the Management Board for the Canadian GEWEX program studying the hydrology and climate of the Mackenzie Basin; Past Secretary and Member of the Scientific Steering Committee for the START international program on building capacity for global change research; and previously as Canadian representative to the UN Framework Convention on Climate Change (responsible for science-related issues); UN/ECE Senior Advisors on Science and Technology; International Institute for Applied Systems Analysis; and NATO Science Committee. He is a member of the Canadian Meteorological and Oceanographic Society.

Bradley H. Udall

Bradley H. Udall (B.S. Stanford, M.B.A. Colorado State University) is the Director of the University of Colorado Western Water Assessment, one of eight National Oceanic and Atmospheric Administration (NOAA)-funded Regional Integrated Sciences and Assessments. Formerly, Mr. Udall was a consulting engineer and principal at Hydrosphere Resource Consultants. As a member of the research faculty at the University of Colorado, Mr. Udall's expertise includes water and policy issues of the American West and especially the Colorado River. He was a co-author of a chapter in a recent Bureau of Reclamation Environmental Impact Statement on incorporating climate change information into future Colorado River planning studies. Mr. Udall has provided testimony for a Senate committee on climate change impacts on water resources. He has received the Climate Science Service Award from the California Department of Water Resources for his work in facilitating interactions between water managers and scientists. Mr. Udall serves on the American Water Works Association Research Foundation expert panel on climate change and serves as an advisor to the Water Utility Climate Alliance.

John E. Walsh

Dr. John E. Walsh is a President's Professor of Global Change at the University of Alaska, Fairbanks and Professor Emeritus of Atmospheric Sciences at the University of Illinois. He is also the Director of the National Oceanic and Atmospheric Administration's (NOAA) Cooperative Institute for Arctic Research at the University of Alaska, and a lead investigator of the Alaska Center for Climate Assessment and Policy, which is Alaska's NOAA-supported Regional Integrated Sciences and Assessments (RISA) center. He received his B.A. in Mathematics at Dartmouth College in 1970 and a Ph.D. in Meteorology at M.I.T in 1974. He served for 30 years on the faculty of the Department of Atmospheric Sciences, University of Illinois, Urbana. His research interests include the climate of the Arctic, especially interactions between the atmosphere and the polar surfaces; extreme weather events as they relate to climate; and climate-cryosphere interactions. Dr. Walsh has published over 100 scientific papers, and he has co-authored a textbook, *Severe and Hazardous Weather.* He was a lead author of the Arctic Climate Impact Assessment (2001-2005) and the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (Working Group II, Polar Regions). He co-chairs the Climate Expert Group of the Arctic Monitoring and Assessment Program, and he is a former member of the Polar Research Board. He is an associate editor of the *Journal of Climate* and a Fellow of the American Meteorological Society.

Michael F. Wehner

Dr. Michael F. Wehner is a member of the Scientific Computing Group at the Lawrence Berkeley National Laboratory in Berkeley, California. He has been active in both the design of global climate models and in the analysis of their output. Under funding from the Department of Energy (DOE) Computer Hardware, Advanced Mathematics and Model Physics program (CHAMMP), he designed the first fully coupled ocean-atmosphere general circulation model to run on distributed memory parallel computers. Later, as part of the DOE Program for Climate Model Diagnosis and

Intercomparison (PCMDI), he developed innovative methods to ascertain the quality of climate model simulations. His current research interests include the statistics of extreme climate events and the quantification of uncertainty in future climate change predictions. A seventeen year veteran of the Lawrence Livermore National Laboratory, he received his doctorate degree in Nuclear Engineering from the University of Wisconsin-Madison in 1983 and joined the Berkeley Laboratory in May, 2002.

Thomas J. Wilbanks

Thomas J. Wilbanks is a Corporate Research Fellow at the Oak Ridge National Laboratory and leads the Laboratory's Global Change and Developing Country Programs. A past President of the Association of American Geographers, he conducts research on such issues as sustainable development, energy and environmental technology and policy, responses to global climate change, and the role of geographical scale in all of these regards. Co-edited recent books include *Global Change and Local Places* (2003), *Geographical Dimensions of Terrorism* (2003), and *Bridging Scales and Knowledge Systems: Linking Global Science and Local Knowledge* (2006). Wilbanks is Chair of the National Research Council's Committee on Human Dimensions of Global Change and a member of a number of other National Academy of Sciences (NAS)/National Research Council (NRC) boards and panels. In recent years, he has been Coordinating Lead Author for the Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report, Working Group II, Chapter 7 (Industry, Settlement, and Society); Coordinating Lead Author for the Climate Change Science Program's (CCSP)Synthesis and Assessment Product (SAP) 4.5 (Effects of Climate Change on Energy Production and Use in the United States); and Lead Author for one of three sections (Effects of Global Change on Human Settlements) of SAP 4.6 (Effects of Global Change on Human Health and Welfare and Human Systems).

Donald J. Wuebbles

Dr. Donald (Don) J. Wuebbles is the Director of the School of Earth, Society, and Environment at the University of Illinois. He is also a Professor in the Department of Atmospheric Sciences as well as in the Department of Electrical and Computer Engineering. He earned his B.S. (1970) and M.S. (1972) degrees in Electrical Engineering from the University of Illinois. He received his Ph.D. in Atmospheric Sciences from the University of California at Davis in 1983. He is the author of almost 400 peer-reviewed scientific articles, most of which relate to atmospheric chemistry and global climate change as affected by both human activities and natural phenomena. He has been a lead author on a number of national and international assessments related to these issues. Dr. Wuebbles was elected a member of the International Ozone Commission in 2000, and in 2005 received the Stratospheric Ozone Protection Award from the U.S. Environmental Protection Agency. He is a Fellow of the American Association for the Advancement of Science and a Faculty Fellow in the National Center for Supercomputing Applications. He has been a lead author on international climate assessments sponsored by the Intergovernmental Panel on Climate Change (IPCC) and thus shares in the Nobel Peace Prize received by IPCC in 2007. Dr. Wuebbles was a leader in assessments of the potential impacts of climate change on the Great Lakes region and on the U.S. Northeast, and recently was co-leader of an assessment of the potential impacts of climate change on the city of Chicago.

Icon	Description	Icon	Description
CCSP 1.1 Temperature Trends	Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences	CCSP 4.3 Impacts	The Effects of Climate Change on Agriculture, Land Resources, Water Resources and Biodiversity
CCSP 1.2 Past Climate	Past Climate Variability and Change in the Arctic and at High Latitudes	CCSP 4.4 Ecosystem Adaptation	Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources
CCSP 1.3 Re-Analysis	Re-Analyses of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change	CCSP 4.5 Energy	Effects of Climate Change on Energy Production and Use in the United States
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CCSP 2.2 Carbon Cycle	North American Carbon Budget and Implications for the Global Carbon Cycle	CCSP 4.7 Transportation	Impacts of Climate Variability and Change on Transportation Systems and Infrastructure -- Gulf Coast Study
CCSP 2.3 Aerosol Impacts	Aerosol Properties and their Impacts on Climate	CCSP 5.1 Data Uses & Limitations	Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions
CCSP 2.4 Ozone Trends	Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, & Implications for Ultraviolet Radiation Exposure	CCSP 5.2 Uncertainty	Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Decisionmaking
CCSP 3.1 Climate Models	Climate Models: An Assessment of Strengths and Limitations	CCSP 5.3 Decision Support	Decision Support Experiments and Evaluations Using Seasonal to Interannual Forecasts and Observational Data
CCSP 3.2 Climate Projections	Climate Projections Based on Emissions Scenarios for Long-Lived Radiatively Active Trace Gases and Future Climate Impacts of Short-Lived Radiatively Active Gases and Aerosols	IPCC WG-1	Working Group I The Physical Science Basis of Climate Change
CCSP 3.3 Extremes	Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands	IPCC WG-2	Working Group II Impacts, Adaptation and Vulnerability
CCSP 3.4 Abrupt Climate Change	Abrupt Climate Change	IPCC WG-3	Working Group III Mitigation of Climate Change
CCSP 4.1 Sea Level Rise	Coastal Elevations and Sensitivity to Sea Level Rise	ACIA Arctic Impacts	Arctic Climate Impact Assessment
CCSP 4.2 Ecosystem Thresholds	Thresholds of Change in Ecosystems	NRC Transportation Impacts	National Research Council, Transportation Research Board: The Potential Impacts of Climate Change on U.S. Transportation, *Climate Variability and Change with Implications for Transportation*

Icon	Description
NAST U.S. Impacts	National Assessment Synthesis Team Climate Change Impacts on the United States: *The Potential Consequences of Climate Variability and Change*
PLACE HOLDER Recent Material	Recent Material Articles recently released
Original Synthesis	Original Synthesis Material synthesized from existing data

FIGURE SOURCES AND PHOTO CREDIT

UNDER DEVELOPMENT

ACRONYMS:

CCSP: Climate Change Science Program
CIESIN: Center for International Earth Science Information Network
CIRES: Cooperative Institute for Research in Environmental Sciences
DOE: Department of Energy
EIA: Energy Information Administration
GAO: General Accounting Office
IARC: International Arctic Research Center
IPCC: Intergovernmental Panel on Climate Change
NASA: National Aeronautics and Space Administration
NASS: National Agricultural Statistics Service
NCDC: National Climatic Data Center
NESDIS: National Environmental Satellite, Data, and Information Service
NOAA: National Oceanic and Atmospheric Administration
NSIDC: National Snow and Ice Data Center
NWS: National Weather Service
PISCO: Partnership for Interdisciplinary Studies of Coastal Oceans
SRH: Southern Regional Headquarter
USDA: United States Department of Agriculture
USDOE: United States Department of Energy
USEPA: United States Environmental Protection Agency
USFS: United States Forest Service
USGS: United States Geological Survey

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