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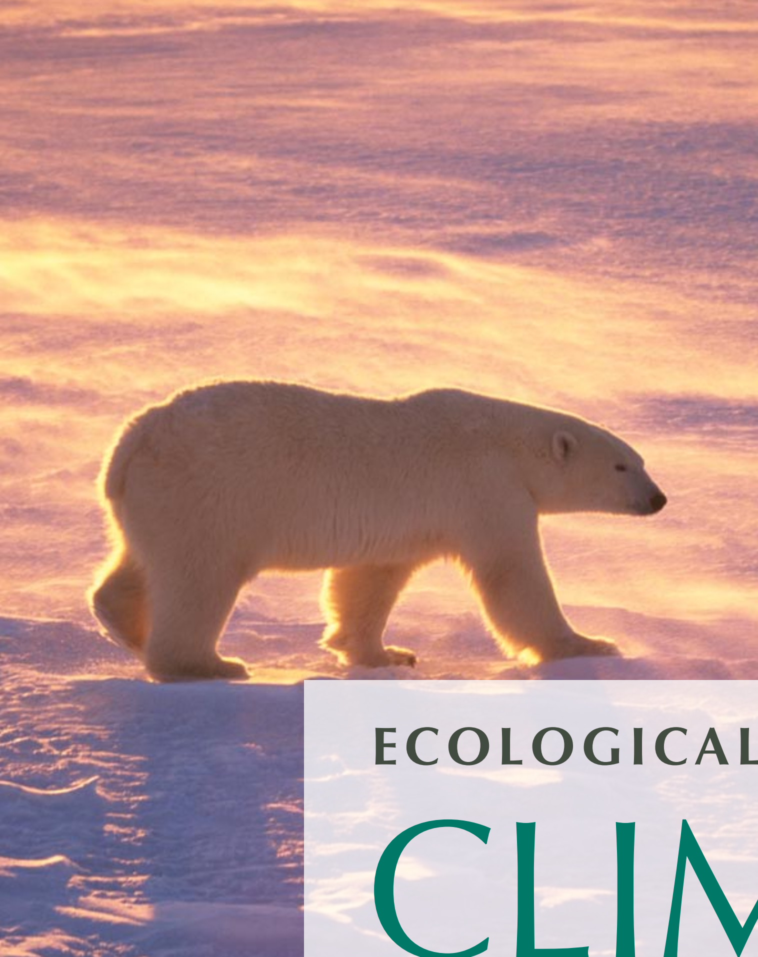
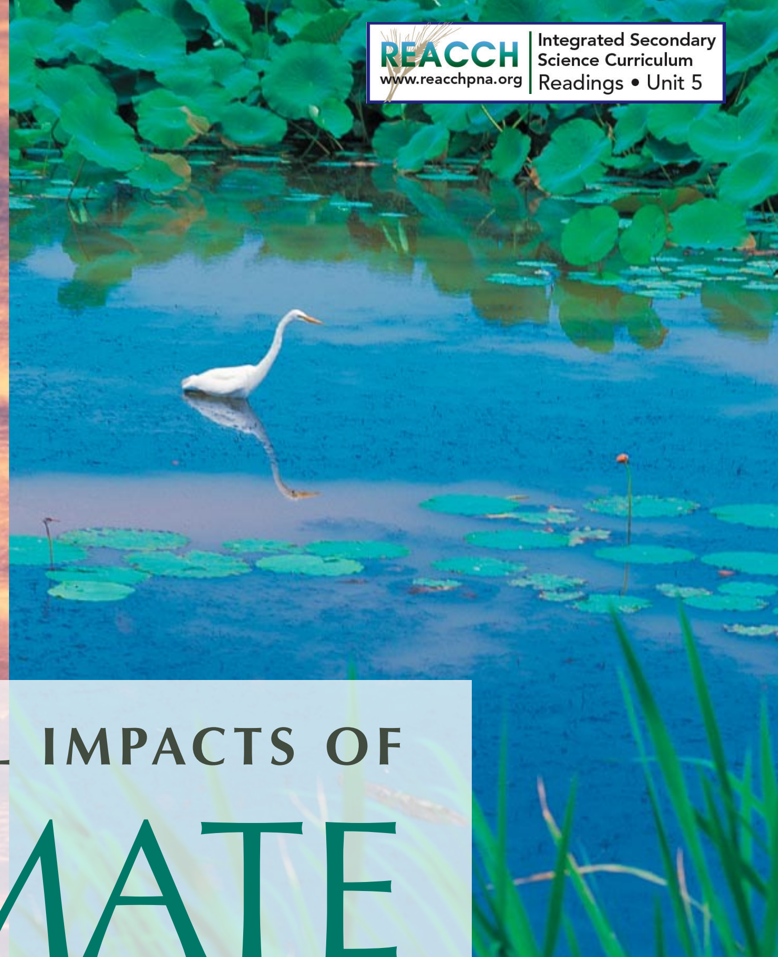
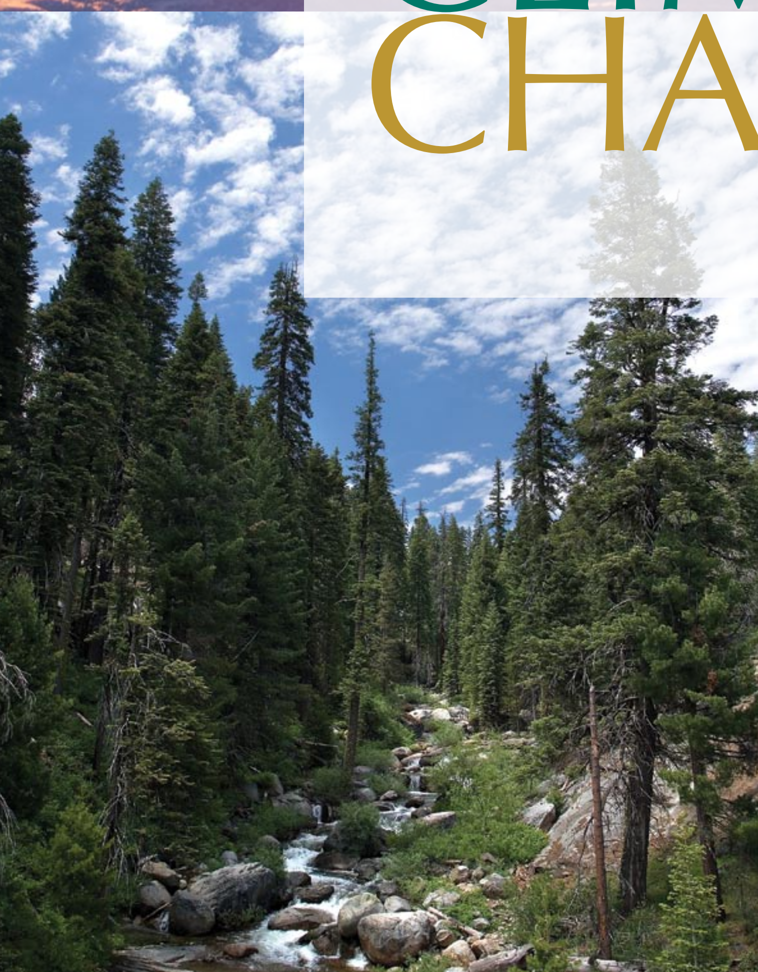



ECOLOGICAL IMPACTS OF CLIMATE CHANGE

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About this Booklet

This booklet is based on the report *Ecological Impacts of Climate Change* (2008), by the Committee on Ecological Impacts of Climate Change. The booklet was developed by Anne Frances Johnson and designed by Francesca Moghari. Funding for the report and this product was provided by the United States Geological Survey.

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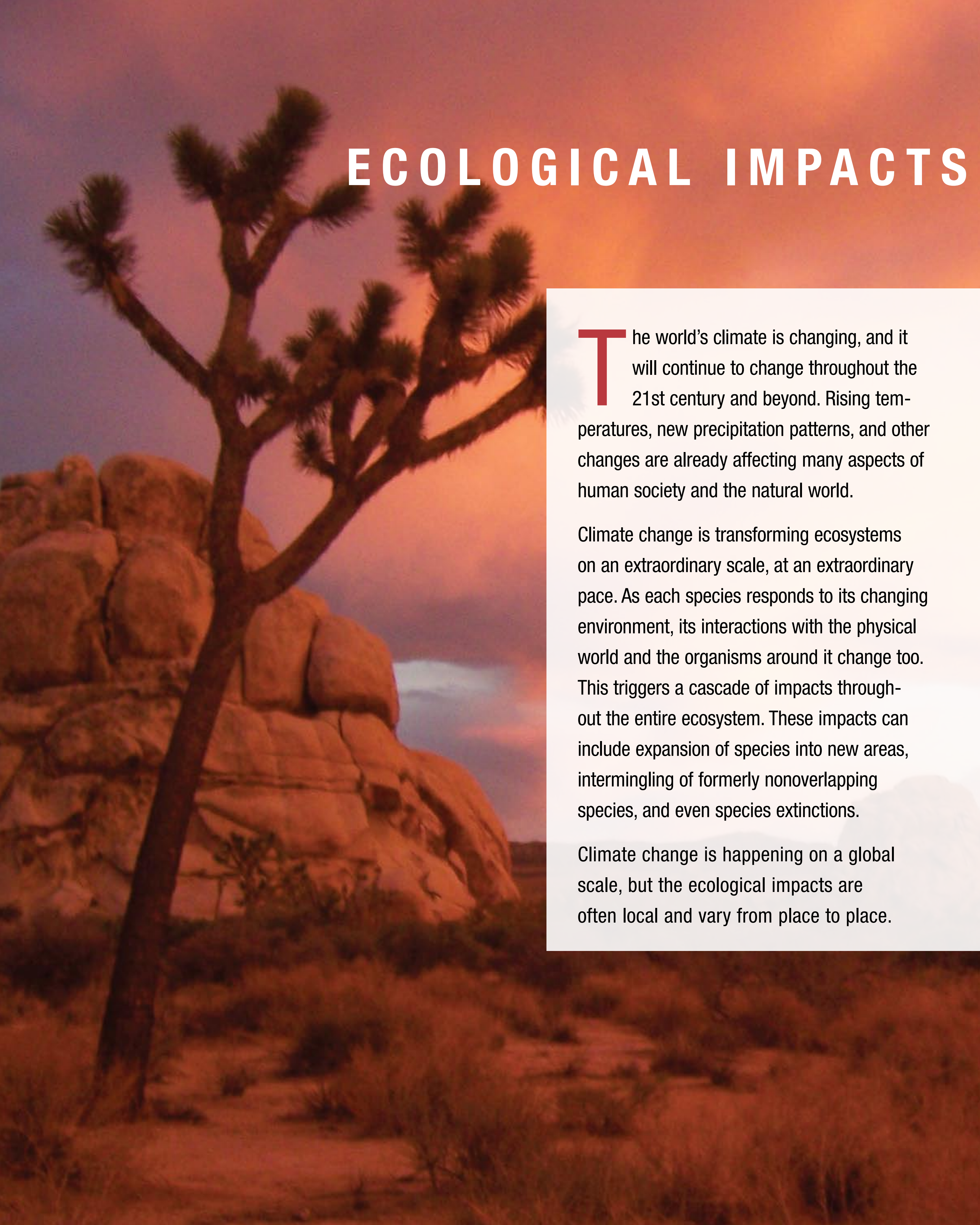


ECOLOGICAL IMPACTS

The world's climate is changing, and it will continue to change throughout the 21st century and beyond. Rising temperatures, new precipitation patterns, and other changes are already affecting many aspects of human society and the natural world.

Climate change is transforming ecosystems on an extraordinary scale, at an extraordinary pace. As each species responds to its changing environment, its interactions with the physical world and the organisms around it change too. This triggers a cascade of impacts throughout the entire ecosystem. These impacts can include expansion of species into new areas, intermingling of formerly nonoverlapping species, and even species extinctions.

Climate change is happening on a global scale, but the ecological impacts are often local and vary from place to place.

OF CLIMATE CHANGE

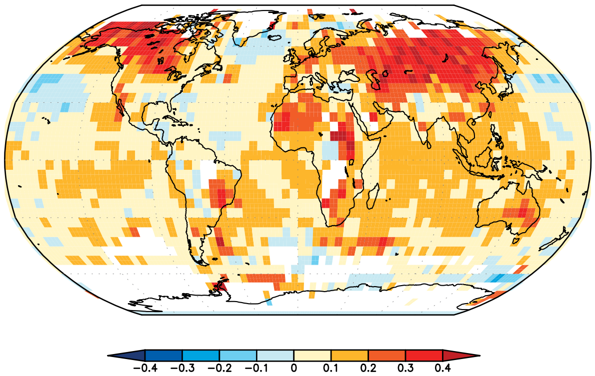
To illuminate how climate change has affected particular species and ecosystems, this booklet presents a series of examples that have already been observed across the United States.

Human actions have been a primary cause of the climate changes observed today. Fortunately, though, humans are also capable of changing their behavior in ways that can reduce the rate of future climate change and help wild species adapt to climate changes that cannot be avoided. How we approach other human activities that affect ecosystems, such as agriculture, water management, transportation, fishing, biological conservation, and many other activities will influence the ways and the extent to which climate change will alter the natural world—and the ecosystems on which we depend.

What Do We Know About Climate Change?

The Earth Is Getting Warmer

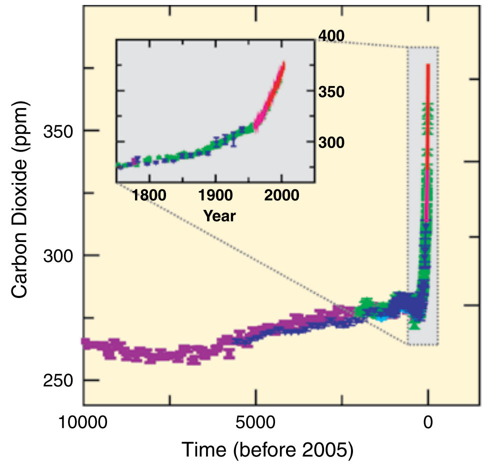
A relatively rapid increase in temperature has been documented during the past century, both at Earth's surface and in the oceans. The average surface temperature for Earth as a whole has risen some 1.3°Fahrenheit since 1850, the starting point for a global network of thermometers. If emission rates for greenhouse gases (which trap heat inside Earth's atmosphere) continue on their current track, models indicate that the globe will be 4.3 to 11.5°F warmer by 2100 than it was in 1990.



The average change in temperature per decade from 1950 to 2005, in degrees Celsius. (If the scale were in °F, it would go from –.72 to .72.)
Image courtesy of the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington.

Human Activities Are Contributing to Climate Change

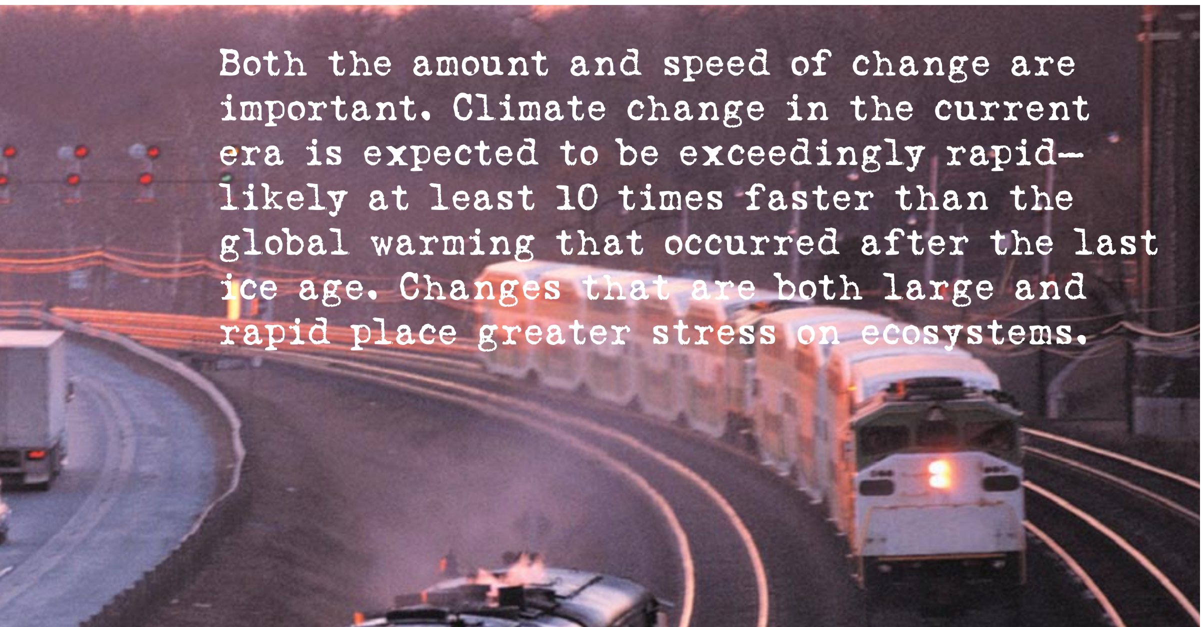
The physical processes that cause climate change are scientifically well documented: both human activities and natural variability are contributing to global and regional warming. According to the Intergovernmental Panel on Climate Change, whose documents are considered the most authoritative source for information on the "state of the science" on climate change, it is very likely that *most* of the observed warming over the past 50 years is the result of increased greenhouse gases generated by human activities. Numerous expert reports from the National Research Council have supported this conclusion as well.



Carbon dioxide and other greenhouse gases, which trap heat inside Earth's atmosphere, have increased dramatically since the Industrial Revolution compared to relatively stable concentrations over the past 10,000 years.
Adapted from Climate Change 2007: The Physical Science Basis. Working Group 1 Contribution to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Figure SPM.5. Cambridge University Press.

The release of greenhouse gases has increased significantly since the Industrial Revolution, mostly from the burning of fossil fuels for energy, agriculture, industrial processes, and transportation. Carbon dioxide, a major greenhouse gas, is increasing in the atmosphere faster than at any time measured in the past, having grown by about 35 percent since 1850. Two other greenhouse gases, methane and nitrous oxide, are present in the atmosphere at much lower concentrations than carbon dioxide but have increased rapidly. Methane has increased by 150 percent; in addition, it is 25 times more effective per molecule at trapping heat than carbon dioxide. Nitrous oxide, nearly 300 times more effective, has increased by more than 20 percent.

Much remains to be learned about the factors that control the sensitivity of climate to increases in greenhouse gases, rates of change, and the regional outcomes of the global changes. Although scientific knowledge of climate is far from complete, the uncertainties concern the details: the scientific community is highly confident in the basic conclusions.



Sea Levels Are Rising

Warmer temperatures not only cause glaciers and land ice to melt (adding more volume to oceans) but also cause seawater to expand in volume as it warms. The global average sea level rose by just under .07 inches per year during the 20th century, but that number has risen to .12 inches per year since the early 1990s. Under a "business-as-usual" greenhouse gas emissions scenario, models indicate that sea levels could rise 2 feet or more by 2100 compared to 1990 levels.

Changes Are Rippling Through the Water Cycle

Climate change has complex effects on water supply and demand. The seasonal rhythms of streams and rivers have changed as winter precipitation falls increasingly as rain instead of snow, and as earlier spring temperatures cause snow in the mountains to melt earlier and faster. Climate change may mean that some places will experience more days with very heavy rain; other places may see more frequent, intense, and long-lasting droughts. Warmer temperatures also mean higher evaporation rates and thirstier plants and people, increasing demands for water. A warmer world will experience more precipitation on a global scale, but the

changes will not be the same everywhere. Projections indicate that on average dry areas will tend to get drier, and wet areas will tend to get wetter.

The Ocean Is Acidifying

Much of the carbon dioxide emitted by human activity has already been taken up by the ocean, thus moderating the increase of carbon dioxide in the atmosphere. However, as carbon dioxide dissolves in seawater, it forms carbonic acid, acidifying the ocean. Ocean acidification will likely cause serious harm to such treasured marine organisms as corals, lobsters, and sea urchins.

Climate Change Is Reflected in Extreme Weather

It is considered very likely that increasing global temperatures will lead to higher maximum temperatures, more heat waves, and fewer cold days over most land areas. More severe drought in some areas, combined with other factors, has contributed to larger and more frequent wildfires.

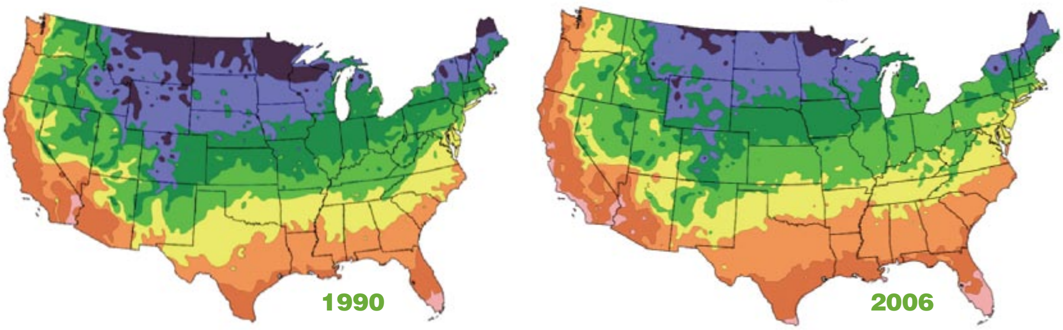
What Are the Ecological Impacts of Climate Change?

Living things are intimately connected to their physical surroundings. Even small changes in the temperature of the air, the moisture in the soil, or the salinity of the water can have significant effects. Each species is affected by such changes individually, but those individual impacts can quickly reverberate through the intricate web of life that makes up an ecosystem.

In particular, two important types of ecological impacts of climate change have been observed across the United States: shifts in species' *ranges* (the locations in which they can survive and reproduce), and shifts in *phenology* (the timing of biological activities that take place seasonally). Examples of these types of impacts have been observed in many species, in many regions, and over long periods of time.

As Earth warms, many species are shifting their ranges to areas with more tolerable climate conditions, in terms of temperature, precipitation, and other factors. About 40 percent of wild plants and animals that have been studied over decades are relocating to stay within their tolerable climate ranges. Some organisms—those that cannot move fast enough or those whose ranges are actually shrinking—are being left with

Many trees are now blooming earlier than they did several decades ago.



Plant hardiness zone maps, used by gardeners to determine which areas are suitable for certain plants. Warmer colors indicate warmer zones. A new map was created in 2006 to reflect changes in climate since the 1990 map was created. Most of the zones shifted northward in this period.
Map courtesy of the National Arbor Day Foundation.

no place to go. For example, as arctic sea ice shrinks, so too shrink the habitats of animals that call this ice home, such as polar bears and seals. As these habitats contract toward the North and South poles, the animals that depend on them will reach the end of the Earth as they know it.

The European pied flycatcher. Its chicks, now born later than the caterpillars on which they feed, are missing the peak of food availability, causing a decline in the bird's population.

Climate change is also driving changes in the timing of seasonal biological activities. Many biological events, especially those in the spring and fall, are based on seasonal cues. Studies have found that the seasonal behaviors of many species now happen 15–20 days earlier than several decades ago. Migrant birds are arriving earlier, butterflies are emerging sooner, and plants are budding and blooming earlier.

If all of the species in an ecosystem shifted their seasonal behavior in exactly the same way, these shifts might not create problems. But when a species depends upon another for survival and only one changes its timing, these shifts can disrupt important ecological interactions, such as that between predators and their prey. For example, a small black-and-white bird called the European pied flycatcher has not changed the time it arrives on its breeding grounds even though the caterpillars it feeds its young are emerging earlier. Missing the peak of food availability means fewer chicks are surviving, in turn causing the flycatcher's population to decline.

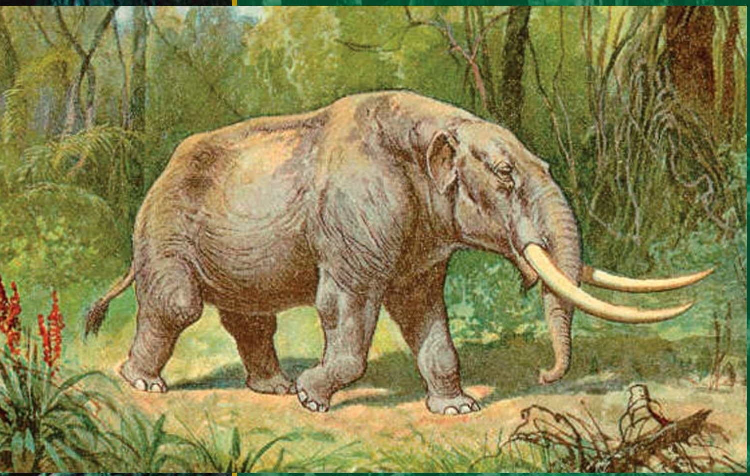
In addition to shifting ranges and seasonal behaviors, other ecological impacts of climate change—some of which will appear in the examples described in this booklet—include changes in growth rates, in the relative abundance of species, in processes like water and nutrient cycling, and in the risk of disturbance from fire, insects, and invasive species.

WINNERS AND LOSERS?

The ecological impacts of climate change are not inherently "bad" or "good." The concept that a change is beneficial or detrimental has meaning mainly from the human perspective. For an ecosystem, responses to climate change are simply shifts away from the system's prior state.

BIODIVERSITY AND THE PERMANENCE OF EXTINCTION

Ecological processes--even those that seem to represent the activities of a single species--depend on interactions among an interconnected web of vital and unique species. Honey, for example, is produced in a beehive, but the bees depend on pollen and nectar from the plants they pollinate. These plants, in turn, depend on the bees that pollinate them, the worms that aerate the soil, the microbes that release nutrients, and many other organisms. This diverse array of creatures is key to the functioning of the entire system.



Artist's depiction of the mastodon, a species driven to extinction by human hunting compounded by a reduction in habitat due to climate change. This example highlights the potentially deadly effects of the combination of climate change and human activities, which are now more varied and pervasive than ever.

Among all the possible impacts of climate change on ecosystems, the most permanent is extinction. Once a species is lost, it cannot be recovered. And since no species lives in isolation, its entire ecosystem can be affected. The number of extinctions caused by climate change so far may be small, but if a level of warming occurs in the range of 3.6 to 5.4°F—somewhere in the low-to-mid projected range—it is estimated that about 20 to 30 percent of studied species could risk extinction in the next one hundred years. Given that there are approximately 1.7 million identified species on the globe, this ratio would suggest that some 300,000 to 600,000 species could be committed to extinction—primarily as a result of human activities.

Other Human Activities Compound the Effects of Climate Change

Plants and animals are simultaneously coping with climate change and many other human-created stresses. Rivers—many of which are polluted by fertilizers or other chemicals—are dammed to provide water for crops or for people. Roads, cities, and farms break up habitats and migration routes, and human activities carry nonnative species into new ecosystems. Many of the species and ecosystems described in this booklet are being affected by these other human influences in addition to those related to climate change.

Ecosystems are generally resilient to some changes. For example, they can often cope with a drought or an unusually hot summer in ways that alter some aspects of the ecosystem but do not cause it to change in a fundamental way. When such changes remain within the limits of an ecosystem's resilience, the ecosystem may not appear to be affected. There is often a threshold point, however, that results in dramatic transformations. Such threshold points are like the moment when water overtops a levee. As long as the water level is even slightly below the top, functioning is normal. But once it rises above the levee, there is a flood—permanently transitioning the ecosystem into a new state. The many ways humans have altered the planet could act as compounding factors that make it harder, or even impossible, for already stressed species to adjust to climate change.

CLIMATE CHANGE IN YOUR BACKYARD

What's Happening across the United States?

Climate change is happening on a global scale, but the ecological impacts are often quite local. This booklet takes a trip across the United States to explore how climate change is affecting ecosystems—including some in our treasured national parks. But remember: Future projections are based on the continuation of current trends in human-caused contributors to climate change. If human activities change, so too may the outcomes.

Edith's and Quino Checkerspot Butterflies

Visitors to California's Yosemite National Park might keep an eye out for a medium-sized butterfly with black, orange, and white patches on its wings flitting among the mountain wildflowers. What makes this species, known as the Edith's checkerspot butterfly, special is its extreme sensitivity to weather and climate, a quality that has turned it into an early warning indicator of climate change in North America.

For more than 40 years, researchers have been tracking Edith's checkerspot butterflies, even dusting off old museum records to determine where the species lived long ago. These investigations have revealed a large-scale shift of the butterfly's range both northward and upward in elevation—in concert with increasing temperature associated with climate change. Although the individual butterflies aren't migrating (they tend to stay in a small area their entire lives), the species' range has shifted as separate populations, one by one, go extinct—four times faster on the southern boundary of their range (Baja, Mexico) than on the northern boundary (in Canada), and nearly three times faster at lower elevations than at higher elevations.

Quino checkerspot, the first endangered species for which climate change is officially listed as both a current threat and a factor to be considered in the plan for its recovery.
Image courtesy of Dr. Gordon Pratt, www.quinocheckerspot.com.

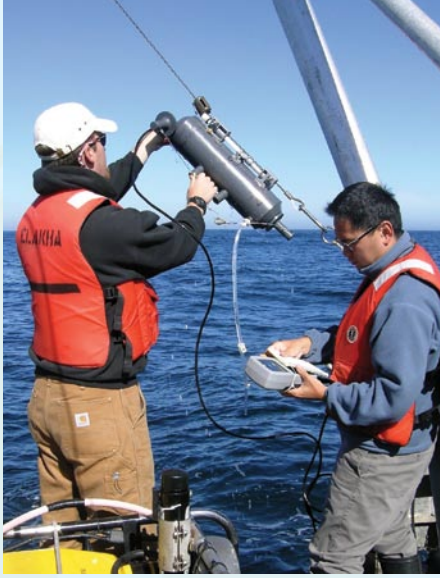
The butterfly's sensitivity to climate is also threatening its survival. A subspecies, the Quino checkerspot, is a federally listed endangered species. Although the primary cause of its decline is habitat destruction, climate change poses problems for its recovery. The southern edge of its range, in Mexico, has the least amount of human development and would offer the best habitat for its recovery, but as a result of climate change, the area is becoming too hot and dry. The Quino checkerspot is the first endangered species for which climate change is officially listed as both a current threat and a factor to be considered in the plan for its recovery.

Pacific Fisheries

Seafood is the primary source of protein for more than 1 billion people worldwide. With demand for seafood growing dramatically, the future of the world's fisheries is of critical importance. Currently, however, there is very limited understanding of how global climate change might affect whole ocean ecosystems.

One effect that has already been observed is a shift in the types of species that are found in certain locations. Among the creatures that inhabit the rocky shorelines of central California, for example, formerly "southern" species have become more abundant since the mid-20th century, while many "northern" species have decreased as the shoreline warms.

Another abnormality that has been linked to climate change is a new "dead zone"—an area of seawater with insufficient oxygen to support most marine life—that has appeared off the coasts of Washington and Oregon. Dead zones suffocate and kill marine organisms that cannot swim or scuttle away fast enough. This dead zone, which has appeared every summer since 2002, is different from most of the other ones around the world because it is not caused by excess nutrients from fertilizer runoff or sewage discharges. Its ultimate cause is still under investigation, but several potential causes are linked to climate change. One possibility is that warmer ocean waters have directly affected the water's ability to hold oxygen at the surface and resupply oxygen to deeper waters. Climate-related changes in coastal winds and ocean circulation may also be responsible.



Scientists retrieve a water sample for research on a recurring "dead zone" off the coasts of Washington and Oregon. The potential causes of the dead zone are linked to climate change.
Image courtesy of Oregon State University.

Wine Quality in California

Some know California as the "Land of Wine and Food," but its premium vineyards could be facing a difficult future. Climate change affects managed ecosystems like vineyards just as it affects natural ecosystems, with corresponding major economic and social implications.

Wine is one of California's most important agricultural products: The industry earns billions of dollars per year and is a critical part of the state's cultural fabric. Wine grapes can grow in a wide range of climates, but the quality of each crop depends on a subtle balance of climate, soils, and landforms. Climate changes during the second half of the 20th century generally improved conditions in California's premium wine regions as the incidence of frost decreased and the growing season began earlier. Further warming, however, would be unlikely to help wine growers in this area. One study concluded that if current greenhouse gas emissions continued, the projected warming would degrade the state's premium wine regions from "optimal" to "marginal" by the end of the 21st century. Another study concluded that the area with the potential to produce premium wines could decrease by up to 81 percent.

Climate change affects managed ecosystems, like vineyards, just as it affects natural ecosystems—with corresponding major economic and social implications.

The Changing Arctic Food Chain

In the Arctic, shrubs are slowly infiltrating territory where once there was only ice, snow, and lichens. Although these unassuming, stunted plants may not seem like much of a threat, their expansion—driven by warming temperatures across the Arctic—is causing a cascade of ecological impacts through the region's food chain.

Caribou—or wild reindeer—are a key species in the arctic ecosystem. They are a critical food source for bears, wolves, and a range of carrion feeders, as well as for indigenous peoples across the region. A warmer climate may help caribou in some ways: Warmer arctic summers tend to increase food availability and, as a consequence, survival of caribou calves. But these advantages are countered by other effects of climate change. Shrubs are crowding out lichens, a key winter food for caribou, and the deep snowdrifts that collect in the shrubs make it harder for caribou to reach the lichens hidden underneath. Additionally, cycles of thawing and refreezing are happening more and more throughout the winter, producing a buildup of ice on top of the snow that makes it difficult for caribou to access the food beneath.

Climate change is affecting caribou (wild reindeer). Although they are enjoying more abundant food in summer, increased shrub growth makes it harder for them to find and reach lichens, their main food source during winter.
Image courtesy of Dean Briggins, U.S. Fish and Wildlife Service.

The increasing number of shrubs is also speeding up the region's rate of warming. Snow trapped by shrubs creates a thick blanket that insulates the soil, keeping it relatively warm over much of the winter. In response, arctic microbes increase their processing of organic matter in the soil, making the soil even more suitable for shrubs to grow, thus further increasing the shrubs' capacity to warm the soil.

Ice-Dependent Animals

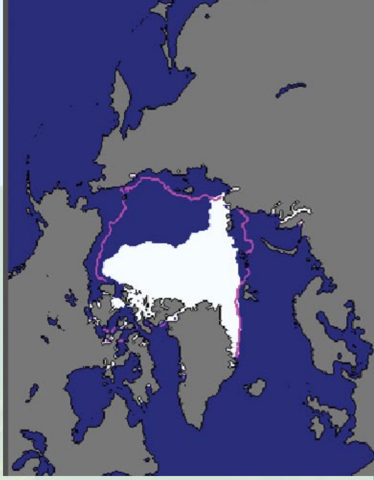
Sea ice is a critical resource for some of the world's most beloved animals. Walruses, for example, use sea ice as nursing platforms for their young and as a hunting base from which they feed on clams and other bottom-dwellers. Each spring, walruses follow their sea ice perches northward as the ice melts off in the south.

Because of climate change, the range of year-round sea ice is shrinking, leading walruses to move farther north each year. In 2007, the ice moved beyond the edge of the continental shelf, where the water becomes too deep for the walruses to feed. For the first time

Melting sea ice threatens ice-dependent animals, such as walruses and polar bears.

in recorded or oral history, thousands of walruses—seeking an alternate place to rest between feeding excursions—set up camp along the beaches near the village of Wainwright, Alaska. This dense aggregation of animals crushed many calves as adults moved to and from the ocean to feed; over time, such a densely packed population could also deplete bottom food resources along the coast.

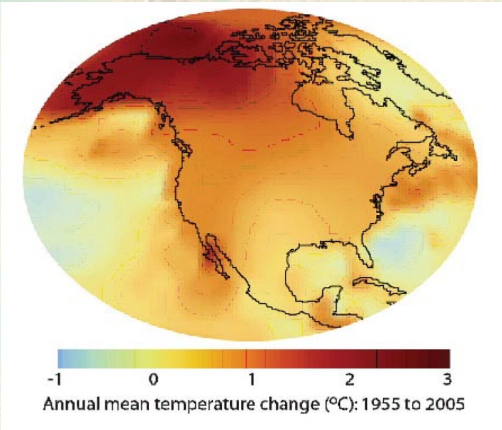
Polar bears also rely on sea ice for hunting. When the sea is covered with ice, bears can wait at openings in the ice for their favorite prey—ringed seals—to surface for air. Where sea ice has melted, leaving only open sea, seals can surface anywhere making it difficult for the polar bears to catch them.



This map shows the average arctic sea ice area for September 2007 (in white) and the average from 1979 to 2000 (pink outline). Image courtesy of the National Snow and Ice Data Center.

A Fast Defrosting Arctic

The Arctic is heating up about twice as rapidly as the rest of the planet. This is due in part to several "feedback loops" in which the consequences of arctic thawing drive temperatures even higher. For example, as sea ice and seasonal snow cover melt, previously reflective white surfaces are converted to darker ocean water or vegetation, respectively. These dark surfaces absorb more solar radiation, leading to higher air temperatures which leads to even more rapid melting, and so on.



The Arctic is warming about twice as fast as the rest of the planet as shown by the large area of dark red. If the scale were in °F, it would go from –1.8 to 5.4. Image created with data from the Goddard Institute for Space Studies.

Thawing permafrost represents another potential feedback loop. Permafrost, the permanently frozen ground found throughout cold regions, contains a great deal of carbon in the form of partially decomposed organic matter. As permafrost warms, the microbes that decompose this material become more active, releasing carbon dioxide and methane into the atmosphere.

A wildfire sweeps through Bitterroot National Forest in Montana.
Image courtesy of John McColgan, USDA Forest Service.

Wildfire, Drought, and Insects

In recent years, visitors to several National Parks, including Zion in Utah and Yosemite in California, have been turned away by nearby wildfires. In addition to their effects on treasured natural areas, wildfires put people, homes, livestock, and businesses at risk. Wildfire is nothing new, but it is dramatically escalating in frequency and extent in western forests, among other areas. There are now four times as many wildfires exceeding 1 ½ square miles as there were 30 years ago, and these frequent large fires are burning six times as much forest area. In the last 20 years, the western fire season has expanded by more than ten weeks.

This increase in wildfire is a legacy of both a changing climate and decades of total fire suppression that has resulted in a buildup of dead fuels. One important factor is drought. Wintertime precipitation is increasingly falling as rain instead of snow, and the snow that does accumulate is melting earlier in the spring—decreasing the amount of water available in the late summer months and contributing to longer and more intense droughts. Compounding the effects of these droughts is the increased susceptibility of drought-stressed trees to attacking insects. In the last decade, a bark beetle epidemic has exploded across 18,000 square miles of western mountain forests. Milder winter temperatures kill fewer beetles in their budworm phase than the colder winters of the past, helping to increase the bark beetle population, with devastating effects. As the beetles kill vast areas of forest, they leave standing dead wood, fueling even larger wildfires.

The climate is becoming too dry to support some of our nation's forests. Ecologists expect that some drought- and wildfire-stricken areas will not recover as forests but will instead regrow as open savannah or grassland ecosystems.

The American pika, a cold-adapted species that is being isolated on mountaintop "islands" by rising temperatures.
Image courtesy of J. R. Douglass, Yellowstone National Park.

The American Pika

Some species that have adapted to living at higher elevations are being stranded on mountaintop "islands." These species can be stuck with nowhere to move as warmer temperatures, and formerly lower-elevation species, creep up to higher elevations. One such species is the American pika, a small-eared relative of rabbits and hares. This species delights visitors to Glacier National Park and other parks throughout the mountain ranges in western states.

Pikas lived in the lowlands during the last ice age. As the ice retreated, these small animals gradually climbed mountain slopes in pursuit of their required climate. Today, the species is restricted to the isolated mountaintop islands as populations below about 7,000 feet rapidly go extinct. The cause, studies suggest, is simple heat stress.

Trout Habitat

Earlier springs and warmer summers are beginning to have a major impact on some of the Rockies' legendary trout streams. With mountain snow melting earlier in the spring, the cool snowmelt water that used to flow through late summer is now slowing to a trickle. In seven Montana rivers, the amount of water flowing in the late summer has dropped on average 30 percent since 1950 as a result of increasing irrigation demand, earlier snowmelt, and warmer summer temperatures. Some small rivers, like Montana's Big Hole, now stop flowing entirely in late summer, shrinking to isolated pools until the autumn rains.

In addition, some streams are reaching high temperatures that are lethal for trout—above 78°F—in July and August. State officials have had to temporarily close some streams to trout fishing during August in recent years because of low stream flow and high water temperatures. Scientists estimate that 18–92 percent of bull trout habitat could be lost in the northern Rocky Mountains in the next half century.

Climate change is altering some trout streams. Here, a family enjoys catch-and-release fishing in Rocky Mountain National Park.

Wildfire and Invasive Species

In the past, the stunning Mojave and Sonoran deserts of the southwestern United States were generally considered fireproof. There simply was not enough fuel to carry a fire through the sparse shrubs and cacti in these unique ecosystems.

Recently, however, some nonnative grasses have become established in these deserts, transforming fireproof desert into highly flammable grassland. For example, buffelgrass, which hails originally from Africa, is spreading rapidly over large parts of the Sonoran Desert. Another grass, known as red brome, is spreading through the Mojave.

These grasses are adapted to fire, sprouting again quickly and densely after a fire sweeps through. Unfortunately, their rapid return pushes out the native species, including the iconic saguaro, or giant, cactus, which is not adapted to frequent fire. While climate change is not directly implicated in the spread of these grasses, scientists are concerned that warming temperatures will allow invasive grasses to spread further in the desert Southwest and to extend into higher elevations.

Invasive grasses are making desert landscapes more prone to fire. Warming temperatures may help these grasses continue to thrive and expand in the American Southwest.
Images courtesy of T. Esque, USGS.

Photos taken from the same vantage point near Los Alamos, New Mexico, in 2002 (left) and in 2004 (right), during and after a major drought devastated the area. Images courtesy of D. Allen, USGS.

The Piñon Pine

Large swaths of the American Southwest are covered with piñon-juniper woodlands—a vegetation type too scrubby to be called a forest but with too many trees to be called a shrubland. As its name implies, it is characterized by two types of evergreens: piñon pines and junipers. Although these plants can typically tolerate drought, extreme conditions can push even these tough species past their limits.

The "Four Corners" region where New Mexico, Arizona, Colorado, and Utah meet is not known for being particularly wet. But the drought that descended on the region from 2000 to 2003 was abnormally severe because it combined low precipitation—25–50 percent less than the long-term average—with unusually high temperatures. By the end of 2003, a large number of the piñons in the region were dead. The main cause of death was infestation by the pine bark beetle, which often targets trees that have been weakened by other stresses—in this case, heat and drought. The widespread loss of these pine trees caused a major ecological change over a large area.

In general, we do not know the thresholds for such major changes before they occur. This example highlights the threat that a stressful event that would not normally trigger a dramatic ecological change may do so when an ecosystem is subject to many interacting stresses.

The Central United States

Agricultural Shifts

The central part of the United States is one of the world's great agricultural regions. Its rich soils and favorable climate produce high yields of corn, soybeans, and wheat. As farming techniques have advanced, farmers have steadily increased yields for these crops over the last century. These continuing efforts to increase yields make it difficult to determine whether or how climate change has affected agriculture thus far, but studies on plant characteristics offer insights as to what farmers might expect from future climate change.

In general, plants grow faster in warmer climates, which could be good news for some farmers, especially in temperate and cold areas. But this applies only up to a point. When it gets too warm, crops tend to mature too early, and under extreme conditions, high temperatures can kill crops. Although different varieties are bred to withstand certain conditions, each crop ultimately has a limited temperature range.

Plants are also affected by the amount of carbon dioxide in the atmosphere. Yields of some crops, such as soybeans and wheat, increase with higher levels of carbon dioxide in the atmosphere, while yields of others, such as sugarcane and corn, do not. Unfortunately for nature lovers who enjoy hiking and exploring, some pest plants—for example, poison ivy—grow faster and produce more irritant when atmospheric carbon dioxide is higher.

Just like natural ecosystems, managed ecosystems such as farmland could face changes associated with shifts in temperature, carbon dioxide concentrations, and many other factors. How farmers adapt to a changing climate will be a critical factor in future crop yields.

Most models conclude that if warming stays within the low-to-mid temperature range of climate change predictions, crop yields will probably increase in the central United States by 5 to 20 percent. But the balance between the effects of warming and the effects of increased carbon dioxide will likely mean increased yields for some crops and decreases for others. Climate change may also alter the dynamics of weeds and other pests and affect the frequency of severe weather events.

How farmers adapt to a changing climate will be a critical factor in future yields. Aggressive action to adjust farming methods, planting dates, and selection of which crops or varieties to grow in response to changing climate conditions can play a large role in future crop yields. Good information about future changes and adaptive measures will be crucial for helping farmers cope effectively with climate change.

Migratory Waterways

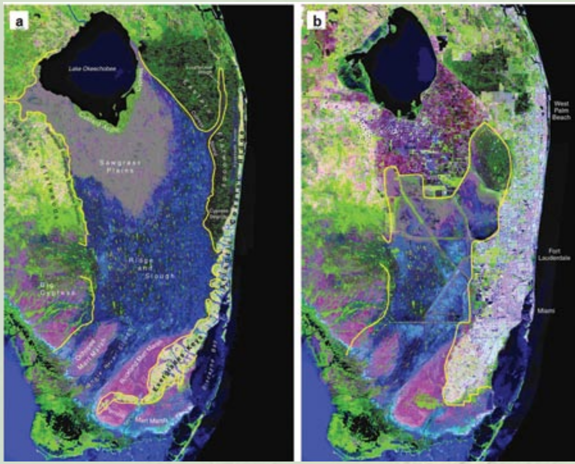
Did you know that the central United States is a critical corridor for millions of migratory birds? During long and exhausting migrations, these birds rest, feed, and mate in a string of small, shallow lakes called "playa lakes" or "prairie potholes." This migration route is especially critical for mallard ducks and other waterfowl, whose yearly populations closely correspond to the number of playa lakes that are available at the beginning of the breeding season.

These crucial watering holes naturally come and go with changing seasons and precipitation patterns. Already under pressure from farmers who use them for irrigation water, from people who fill them in to create more land for crops or houses, and from contaminated runoff of nutrients and pesticides, these essential but transient habitats are expected to face increased stress due to climate change. A combination of higher temperatures and lower rainfall could literally dry up the playa lakes in six states, posing a significant threat to the birds that depend on them.

These shallow, temporary lakes scattered throughout the Midwest provide critical places for migrating birds to rest, feed, and mate.
Image courtesy of the U.S. Fish and Wildlife Service.

The Florida Everglades and Sea-Level Rise

Visitors to Everglades National Park come to marvel at vast swamps that are home to wading birds, alligators, wood storks, Florida panthers, and manatees. But the region known as the Everglades has undergone dramatic changes over the past 100 years, shrinking to half its original size. These changes are primarily the result of human manipulation and pollution of the region's most critical resource—water. There are ongoing efforts to restore the ecosystem, but increasing water temperatures, changes in precipitation, and more extreme storms will likely make restoration more difficult.

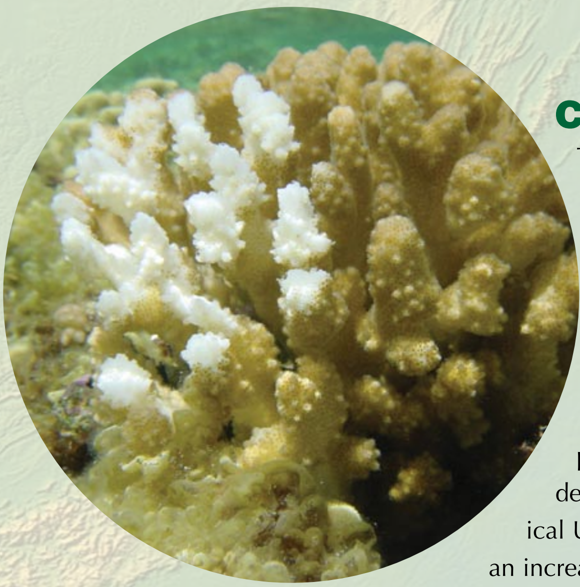


Reconstructed satellite images show the Everglades of the 1850s (left) and present day (right). The yellow lines are the historical and current border of the Everglades ecosystem.
Image courtesy of the South Florida Water Management District.

One major change that could affect the Everglades and other unique ecosystems is sea-level rise. Sea-level rise can increase the salt content of existing bodies of fresh water and could cause existing dry ecosystems to find themselves under water by the end of this century. Some regions of the Gulf Coast are simultaneously being affected by sea-level rise and subsidence, or sinking, of the land. In these areas, the water level is projected to rise 2–4 feet over this century—reconfiguring shorelines and fragmenting barrier islands.

Some mangroves and marshes—two types of plant community specially adapted to the conditions at the borders between land and sea—are moving inland in response to sea-level rise. Unfortunately, roads and buildings in highly developed areas make this adaptation strategy more difficult. Additionally, a rapid *rate* of future climate change would leave many mangroves and marshes hard-pressed to move fast enough to compensate for those that are lost to the sea.

Mangroves like this one are specially adapted to living at the edge of the ocean. But rising seas may soon threaten these and other coastal ecosystems.



A partially bleached coral. Coral bleaching, which results from warmer water temperatures, can be deadly to the corals if it lasts too long.
Image courtesy of NOAA.

Coral Reefs

The coral reefs of Biscayne National Park, just miles from downtown Miami, Florida, attract more than half a million visitors per year. In addition to drawing crowds for their dazzling natural beauty, coral reefs play some important roles in the marine ecosystem. For example, they provide key habitat for fish and act as a protective barrier for nearby shores. Unfortunately, overfishing, pollution, and coastal development are already degrading reefs off the Florida Keys and in other tropical U.S. waters. Climate and associated changes pose an increasing threat to their survival.

The shallow tropical waters in which most corals are found are warming. Heat stress causes corals to expel the symbiotic algae that provide their primary source of nutrition, leaving only the white "bones" of the corals behind. This process, called coral bleaching, can be lethal to the coral if it lasts too long. Coral bleaching, which has increased in recent decades, becomes worse as high temperatures last longer and longer.

Corals are also being affected by ocean acidification, which is caused by the increase in carbon dioxide in the atmosphere. This affects the ability of marine organisms to build their shells and skeletons. Ocean acidification is likely to slow, or even stop, the growth of coral over this century. This would not only affect the corals themselves but also put in jeopardy the survival of the myriad species found only on coral reefs.

Northward Movement of Tropical Species

Tropical species are moving northward into the southern United States, delighting bird and butterfly watchers alike. Former migrants like the rufous hummingbird and the Mexican green jay have become year-round residents in Alabama and Texas, respectively. Florida has five new species of tropical dragonfly, and many tropical butterflies normally confined to Mexico are starting to breed as far north as Austin, Texas.

Some tropical species, like this rufous hummingbird, are moving northward to the delight of bird and butterfly watchers in the Southeast.
Image courtesy of Dean E. Briggins, U.S. Fish and Wildlife Service.

The Northeast

Northeast Fisheries

Fisheries are a major part of New England's economy, history, and culture, but some species are under pressure from overfishing. Some of the region's most-important fish species are known to be affected by water temperature. Adult cod, for example, require bottom-water temperatures cooler than 54°F; their young require water cooler than 46°. Substantial ocean warming could restrict cod to living only in cooler pockets in northern areas and Georges Bank.

Lobstermen unload the day's catch. Warming waters could have an impact on New England's famous lobster fishery.

Lobsters, another key species for northeast fisheries, tolerate a wider range of water temperatures than do cod. In warmer water, however, lobsters need more oxygen to survive. This requirement, combined with the fact that warmer water holds less oxygen, makes the concentration of oxygen in the water insufficient for lobsters at about 79°F. Since the late 1990s, lobster populations in Long Island Sound have fallen precipitously. While many factors may have contributed to this decline, warming is probably part of the mix: water temperatures have exceeded 79°F with increasing frequency. On the other hand, northward, in the Gulf of Maine, warmer conditions could improve lobster habitat—supporting a longer growing season, faster lobster growth, and larger area suitable for juveniles to grow in.

Some dangerous animal parasites are moving northward in response to warming waters, with potentially major impacts on fisheries. One example is the oyster parasite *Perkinsus marinus*, which can cause mass oyster deaths. This parasite has extended its range northward from Chesapeake Bay to Maine—a 310-mile shift linked to above-average winter temperatures.

What Does the Future Hold . . .
and What Can We Do?

Predicting the Future: Lessons from the Distant Past

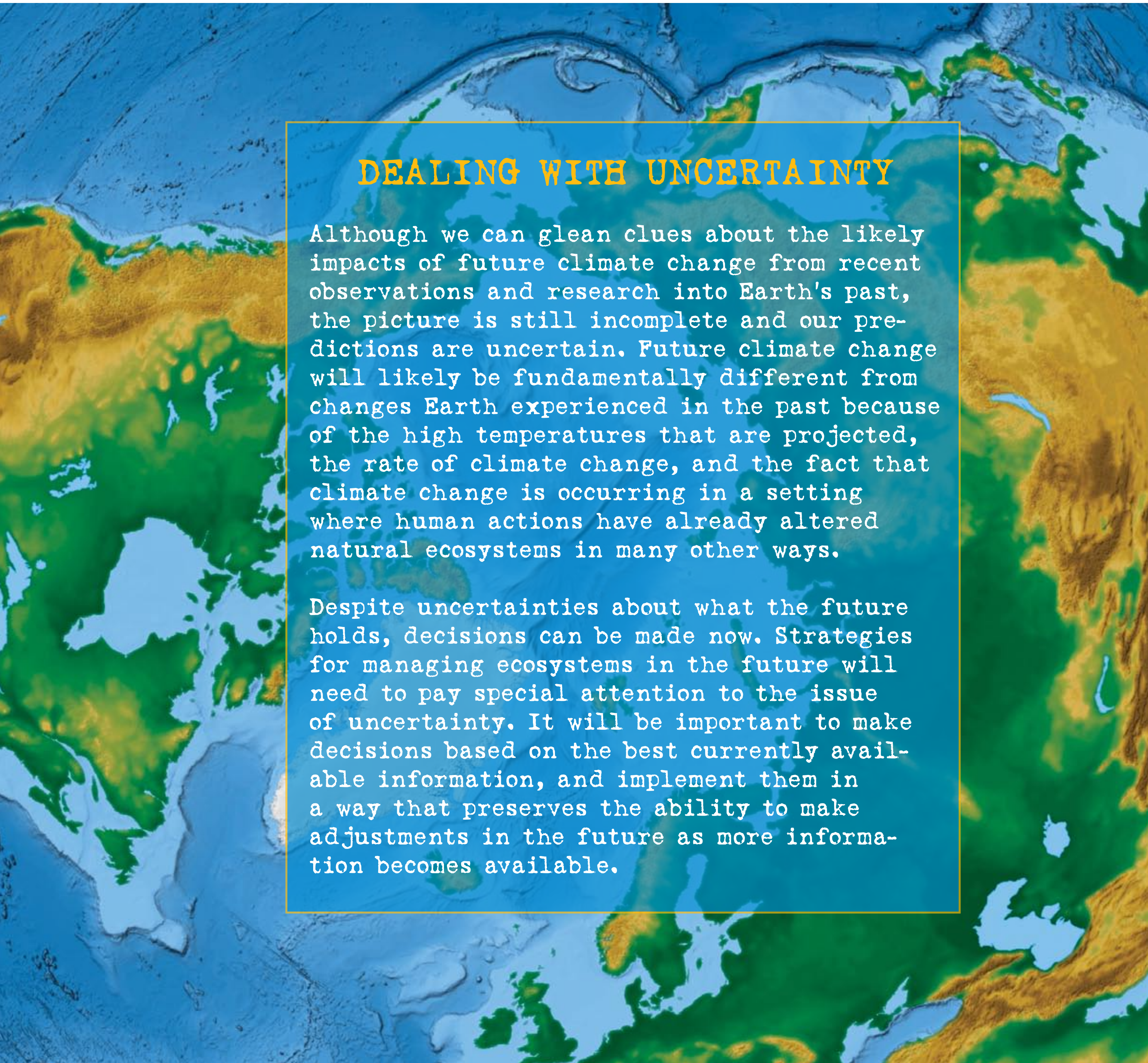
Our ability to predict future ecological impacts of climate change stems largely from what we know about the past. Rocks, ice cores, cave formations, tree rings, sediments, and other natural "climate recorders" have offered clues about how ecosystems respond to major climate shifts.

Earth has experienced a series of ice ages over the past million years. Around 21,000 years ago—during the peak of the last ice age—most of Canada and the northern United States was under thousands of feet of ice. Arctic vegetation thrived in Kentucky, and sea levels were about 400 feet lower than today. That ice age ended as subtle changes in the Earth's orbit slowly warmed the globe. This and other periods of cooling and warming caused widespread ecological changes: Some ecosystems shifted to locations with more favorable conditions, others vanished, and new types of ecosystems emerged.

A scientist in the US Geological Survey National Ice Core Lab. Ice cores, which are samples taken from polar ice caps and mountain glaciers, provide clues about changes in Earth's climate and atmosphere going back thousands of years.

Climate change in the coming decades could be much more rapid on a sustained, global basis than the transitions into and out of many past ice ages. In past ice ages, ecosystems were pushed off large swaths of Earth's surface as ice-dominated landscapes advanced, but when the change was slow enough—over many thousands of years—similar ecosystems reassembled again as the ice retreated. There have also been abrupt changes in the past, but the rate of change in the current era is expected to be both global and rapid. Ecosystems can be particularly vulnerable when major climate changes happen over a relatively shorter period of time.

One of the major concerns about the future is that climate changes may happen too fast to allow many organisms to respond. Some individuals and species can adapt or move faster or farther than others. For example, a long-lived tree species may take decades to shift to a new range, while an insect species could shift its range much more quickly. Understanding how quickly species and ecosystems can adjust is one of the key challenges in climate change research.



DEALING WITH UNCERTAINTY

Although we can glean clues about the likely impacts of future climate change from recent observations and research into Earth's past, the picture is still incomplete and our predictions are uncertain. Future climate change will likely be fundamentally different from changes Earth experienced in the past because of the high temperatures that are projected, the rate of climate change, and the fact that climate change is occurring in a setting where human actions have already altered natural ecosystems in many other ways.

Despite uncertainties about what the future holds, decisions can be made now. Strategies for managing ecosystems in the future will need to pay special attention to the issue of uncertainty. It will be important to make decisions based on the best currently available information, and implement them in a way that preserves the ability to make adjustments in the future as more information becomes available.

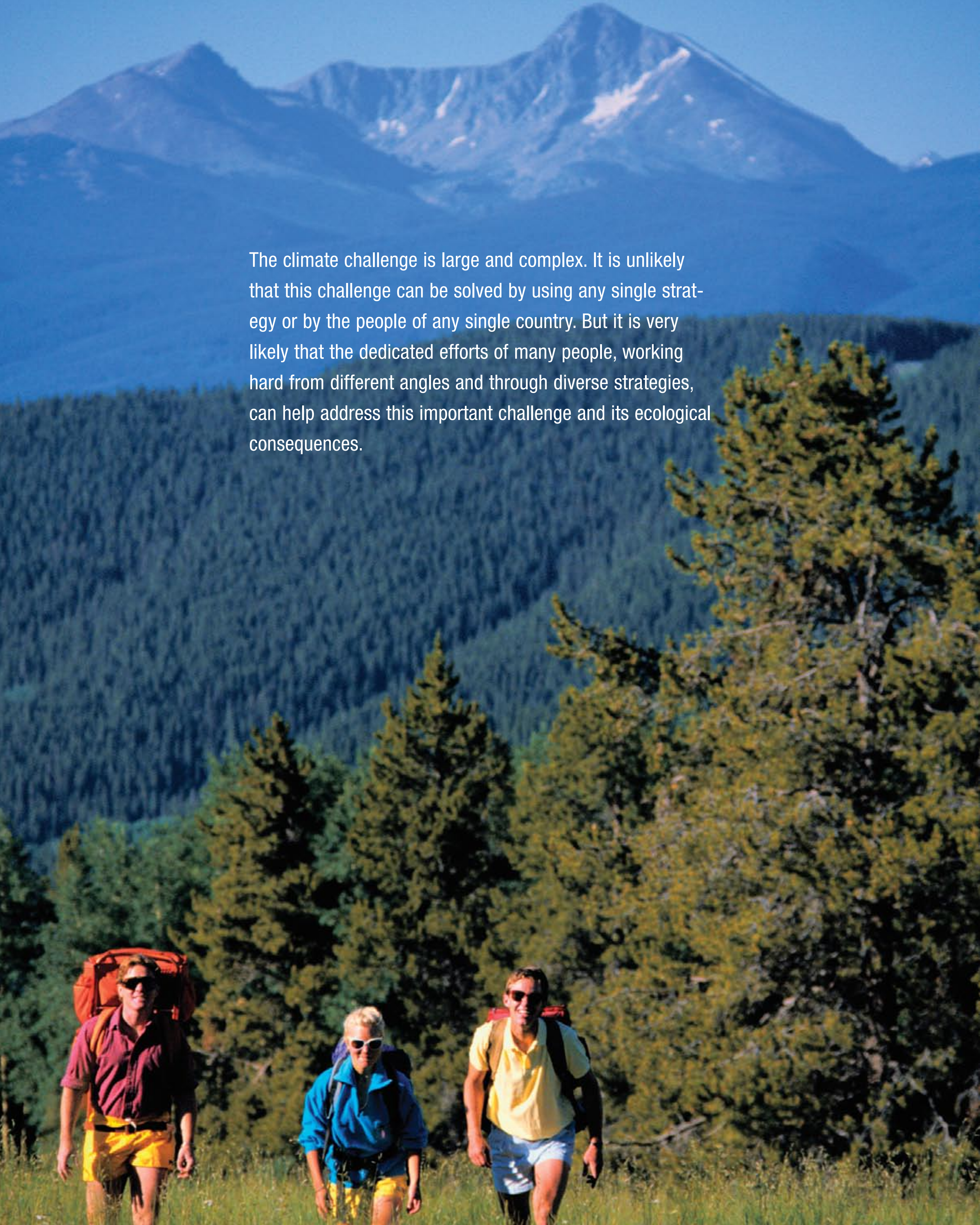
Human Causes, Human Solutions

Climate change is one of the defining issues of the 21st century. Decisions about climate change over the coming decades will likely reverberate through centuries: it is generally agreed that a change in such factors as carbon dioxide emission rates would change the projected outcomes.

Humans are challenged to find a set of policies, practices, and standards of behavior that provide long-term economic opportunities and improved quality of life around the world while maintaining a sustainable climate and viable ecosystems. Recent analyses by U.S. and international experts conclude that the world should invest in minimizing the amount of climate change that occurs and in adapting to the changes that cannot be avoided. The appropriate level, financing, and structure of these investments are questions to be discussed among all members of society.

Some of the issues are so big that the involvement of governments will be required. These include decisions about the best ways to reduce a country's carbon emissions and where to invest funds in research on alternative energy sources. Other decisions are best addressed at the individual, family, or business level. Each time a car, home appliance, or lightbulb is purchased, a decision is made that has a small influence on climate change. But many small decisions, made by billions of people, can combine to have very large effects.

We know that climate change is not the only stress ecosystems are facing. An important way for society to help reduce the ecological impacts of climate change is by creating conditions that make it easier for species in ecosystems to adapt—that is, by reducing other human-influenced ecosystem stresses. Well-thought-out approaches to and investment in conservation, sustainable agricultural practices, pollution reduction, and water management can all help ecosystems withstand the impacts of a changing climate.



The climate challenge is large and complex. It is unlikely that this challenge can be solved by using any single strategy or by the people of any single country. But it is very likely that the dedicated efforts of many people, working hard from different angles and through diverse strategies, can help address this important challenge and its ecological consequences.

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Life on Earth is profoundly affected by the planet's climate. Animals, plants, and other living beings around the globe are moving, adapting, and, in some cases, dying as a direct or indirect result of environmental shifts associated with our changing climate—disrupting intricate interactions among Earth's species, with profound implications for the natural systems on which humans depend.

Climate change is happening on a global scale, but the ecological impacts are often local. To illuminate how climate change has affected species and ecosystems across the United States, this booklet, based on the conclusions of an independent, expert committee of the nation's leading scientists, describes some of the ecological impacts of climate change that have already been observed right in our own backyard.

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