Introduction

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 at extraordinary rates and scales. As each species responds to its changing environment, its interactions with the physical world and the creatures around it change—triggering a cascade of impacts throughout the ecosystem, such as expansion into new areas, the intermingling of formerly non-overlapping species, and even species extinctions

Climate change is a global-scale process, but with diverse regional manifestations. The ecological impacts are typically local and vary from place to place. To illuminate how climate change has affected specific species and ecosystems, this document presents a series of examples of ecological impacts of climate change that have already been observed across the United States.

Human actions have been a primary cause of the climate changes observed today, but humans are capable of changing our behavior in ways that modify the rate of future climate change. Human actions are also needed to help wild species adapt to climate changes that cannot be avoided. Our approaches to energy, agriculture, water management, fishing, biological conservation, and many other activities will all affect the ways and extent to which climate change will alter the natural world—and the ecosystems on which we depend.

What are ecosystems and why are they important?

Humans share Earth with a vast diversity of animals, plants, and microorganisms. Virtually every part of the planet—the continents, the oceans, and the atmosphere—teems with life. Even the deepest parts of the ocean and rock formations hundreds of meters below the surface are populated with organisms adapted to cope with the unique challenges that each environment presents. In our era organisms almost everywhere are facing a new set of challenges; specifically, the challenges presented by rapid climate change. How have plants, animals, and microorganisms coped with the climate changes that have already occurred, and how might they cope with future changes? To explore these questions we start with a discussion of how plants, animals, and microorganisms fit together in ecosystems and the role of climate in those relationships.

Earth has a great diversity of habitats. These differ in climate, of course, but also in soils, day length, elevation, water sources, chemistry, and many other factors, and consequently, in the kinds of organisms that inhabit them. The animals, plants, and microorganisms that live in one place, along with the water, soils, and landforms, make an ecosystem. When we attempt to understand the impacts of climate change, thinking about ecosystems—and not just individual species—can be helpful because each ecosystem depends on a wide array of interactions among individuals. Some of these involve competition. For example, some plants shade others or several animals compete for the same scarce food. Some involve relationships between animals and their prey. Others involve decomposition, the process of decay that returns minerals and organic matter to the soil. And some interactions are beneficial to both partners, for example, bees that obtain food from flowers while pollinating them.

Climate influences ecosystems and the species that inhabit them in many ways. In general, each type of ecosystem is consistently associated with a particular combination of climate characteristics (Walter 1968). Warm tropical lands with year-round rain typically support tall forests with evergreen broadleaved trees. Midlatitude lands with cold winters and moist summers usually support deciduous forests, while drier areas are covered in grasslands, shrublands, or conifer forests. In a similar fashion shallow tropical-ocean waters harbor coral reefs on rocky bottoms and mangrove forests along muddy shores, whereas temperate shores are characterized by kelp forests on rocky bottoms and seagrasses or salt marshes on sediment-covered bottoms. These major vegetation types or biomes can cover vast areas. Within these areas a wide range of subtly different ecosystems utilize sites with different soils, topography, land-use history, ocean currents, or climate details. Humans are an important part of most ecosystems, and many ecosystems have been heavily modified by humans. A plot of intensively managed farmland, a fish pond, and a grazed grassland are just as much ecosystems as is a pristine tropical forest. All are influenced by climate, all depend on a wide variety of interactions, and all provide essential benefits to people.

The lives of animals, plants, and microorganisms are strongly attuned to changes in climate, such as variation in temperatures; the amount, timing, or form of precipitation; or changes in ocean currents. Some are more sensitive and vulnerable to climate fluctuations than others. If the climate change is modest and slow, the majority of species will most likely adapt successfully. If the climate change is large or rapid, more and more species will face ecological changes to which they may not be able to adapt. But as we will see later, even modest impacts of climate change can cause a range of significant responses, even if the changes are not so harsh that the organism dies. Organisms may react to a shift in temperature or precipitation by altering the timing of an event like migration or leaf emergence, which in turn has effects that ripple out to other parts of the ecosystem. For example, such timing changes may alter the interactions between predator and prey, or plants (including many crops) and the insects that pollinate their flowers. Ultimately we want to understand how climate change alters the overall functioning of the ecosystem and in particular how it alters the ability of the ecosystem to provide valuable services for humans.

Ecosystems play a central role in sustaining humans (Figure 1) (Daily 1997; Millennium Ecosystem Assessment 2005). Ecosystems *provide products* directly consumed by people. This includes food and fiber from agricultural, marine, and forest ecosystems, plus fuel, including wood, grass, and even waste from some agricultural crops, and medicines (from plants, animals and seaweeds). Our supply and quality of fresh water also depends on ecosystems, as they play a critical role in circulating, cleaning, and replenishing water supplies. Ecosystems also *regulate our environment*; for example, forests, floodplains, and streamside vegetation can be critically important in controlling risks from floods; likewise, mangroves, kelp forests, and coral reefs dampen the impact of storms on coastal communities. Ecosystems provide cultural services that *improve our quality of life* in ways that range from the sense of awe many feel when looking up at a towering sequoia tree to educational and recreational opportunities. Ecosystems also *provide nature's support structure*; without ecosystems there would be no soil to support plants, nor all the microorganisms and animals that depend on plants. In the oceans, ecosystems sustain the nutrient cycling that supports marine plankton, which in turn supply food for the fish and other seafood humans eat. Algae in ocean ecosystems produce much of the oxygen that we breathe. In general, we do not pay for the services we get from ecosystems, even though we could not live without them and would have to pay a high price to provide artificially.

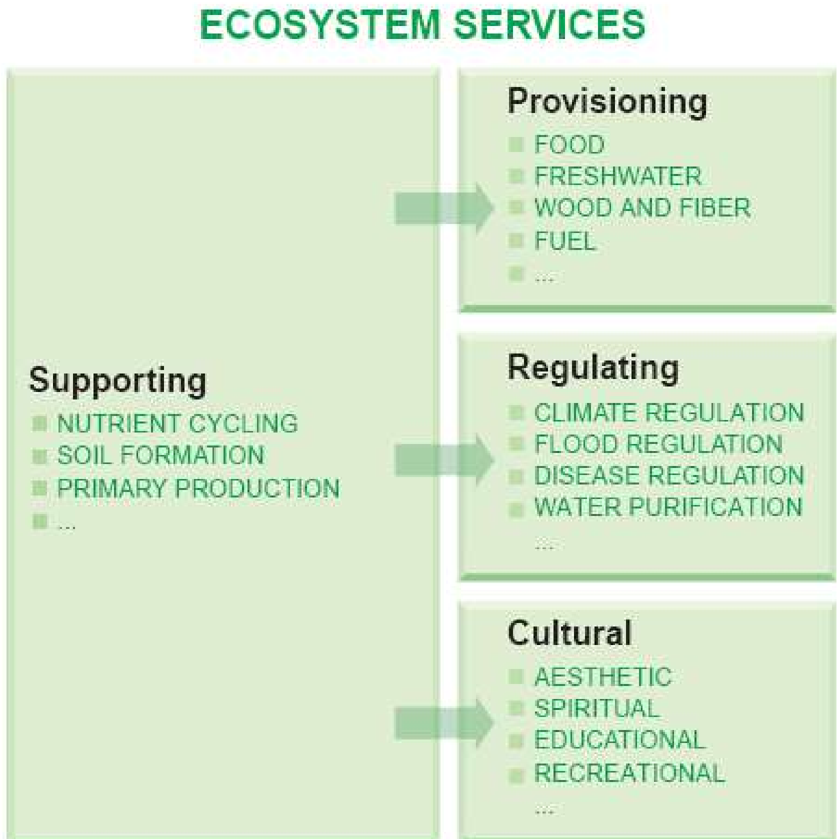


FIGURE 1 Ecosystem services. SOURCE: Millennium Ecosystem Assessment (2005).

Ecosystem services rely on complex interactions among many species, so in most environments it is critical that they contain a diverse array of organisms. Even those services that appear to depend on a single species, like the production of honey, actually depend on the interactions of many species, sometimes many hundreds or thousands. Honey comes from honeybees, but the bees depend on pollen and nectar from the plants they pollinate. These plants depend not only on the bees but also on the worms and other soil animals that aerate the soil, the microorganisms that release nutrients, and the predatory insects that limit populations of plant-eating insects. Scientists are still at the early stages of understanding exactly how diversity contributes to ecosystem resilience—the ability of an ecosystem to withstand stresses like pollution or a hurricane without it resulting in a major shift in the ecosystem's type or the services it provides (Schulze and Mooney 1993; Chapin et al. 1997; Tilman et al. 2006; Worm et al. 2006). But we are already certain about one thing. Each species is a unique solution to a challenge posed by nature and each species' DNA is a unique and complex blueprint. Once a species goes extinct, we can't get it back. Therefore, as we look at the impacts of climate change on ecosystems, it is critical to remember that some kinds of impacts—losses of biological diversity—are irreversible.

What do we know about current climate change?

Over the last 20 years the world's governments have requested a series of authoritative assessments of scientific knowledge about climate change, its impacts, and possible approaches for dealing with climate change. These assessments are conducted by a unique organization, the Intergovernmental Panel on Climate Change (IPCC). Every five to seven years, the IPCC uses volunteer input from thousands of scientists to synthesize available knowledge. The IPCC conclusions undergo intense additional review and evaluation by both the scientific community and the world's governments, resulting in final reports that all countries officially accept (Bolin 2007). The information in the IPCC reports has thus been through multiple reviews and is the most authoritative synthesis of the state of the science on climate change.

Earth's average temperature is increasing

In 2007 the IPCC reported that Earth's average temperature is unequivocally warming (IPCC 2007b). Multiple lines of scientific evidence show that Earth's global average surface temperature has risen some 0.75°C (1.3°F) since 1850 (the starting point for a useful global network of thermometers). Not every part of the planet's surface is warming at the same rate. Some parts are warming more rapidly, particularly over land, and a few parts (in Antarctica, for example) have cooled slightly (Figure 2). But vastly more areas are warming than cooling. In the United States average temperatures have risen overall, with the change in temperature generally much higher in the northwest, especially in Alaska, than in the south (Figure 3). The eight warmest years in the last 100 years, according to NASA's Goddard Institute for Space Studies, have all occurred since 1998 (http://www.giss.nasa.gov/research/news/20080116/).

During the second half of the 20th century, oceans have also become warmer. Warmer ocean waters cause sea ice to melt, trigger bleaching of corals, result in many species shifting their geographic ranges, stress many other species that cannot move elsewhere, contribute to sea-level rise (see below), and hold less oxygen and carbon dioxide.

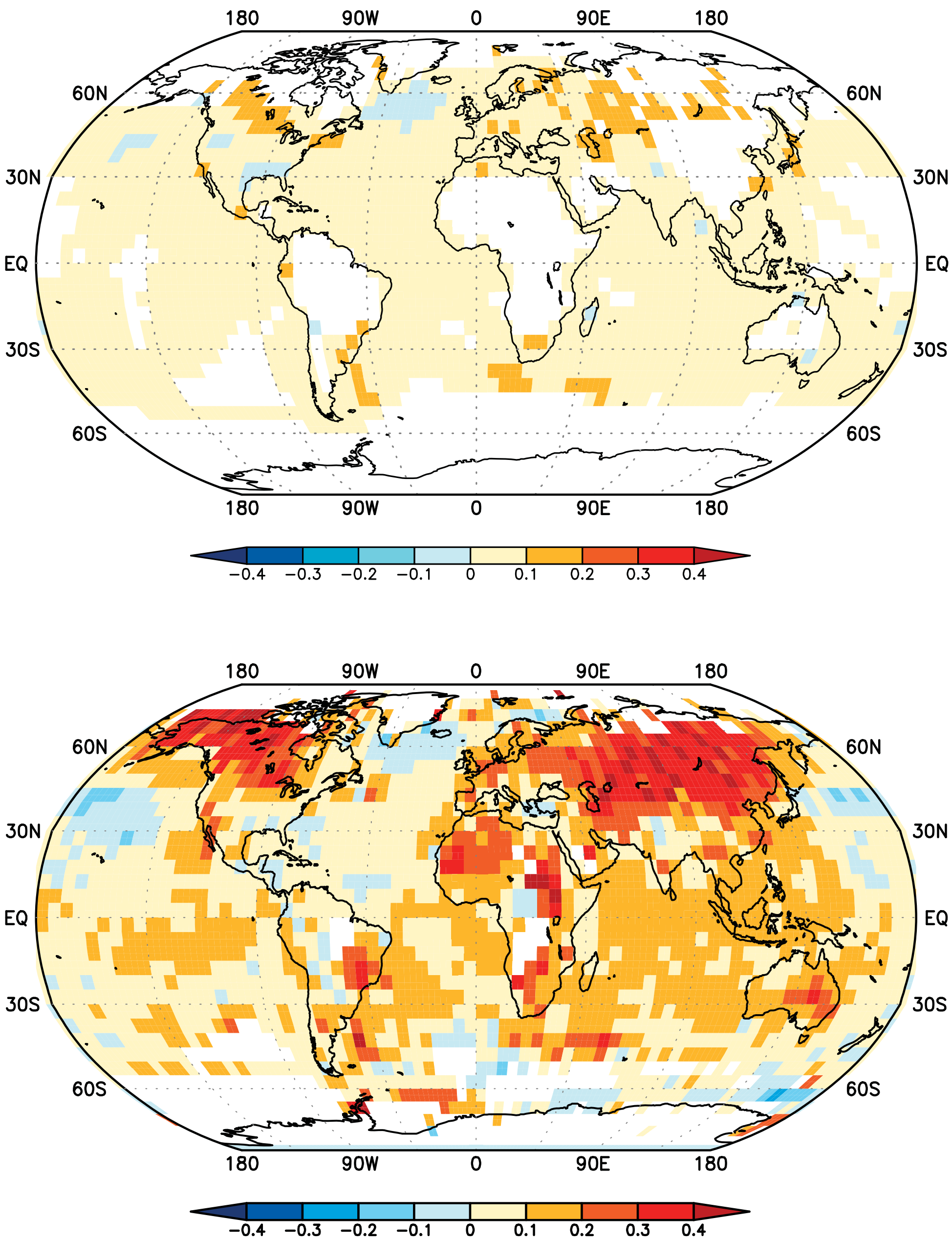


FIGURE 2 Global trends in temperature. The upper map shows the average change in temperature per decade from 1870 to 2005. Areas in orange have seen temperatures rise between 0.1-0.2^{o}C per decade, so that they average 1.35 to 2.7^{o}C warmer in 2005 than in 1870. The lower map shows the average change in temperature per decade from 1950 to 2005. Areas in deep red have seen temperatures rise on average more than 0.4^{o}C per decade, so that they average more than 2^{o}C warmer in 2005 than in 1950. SOURCE: Joint Institute for the Study of the Atmosphere and Ocean, University of Washington.

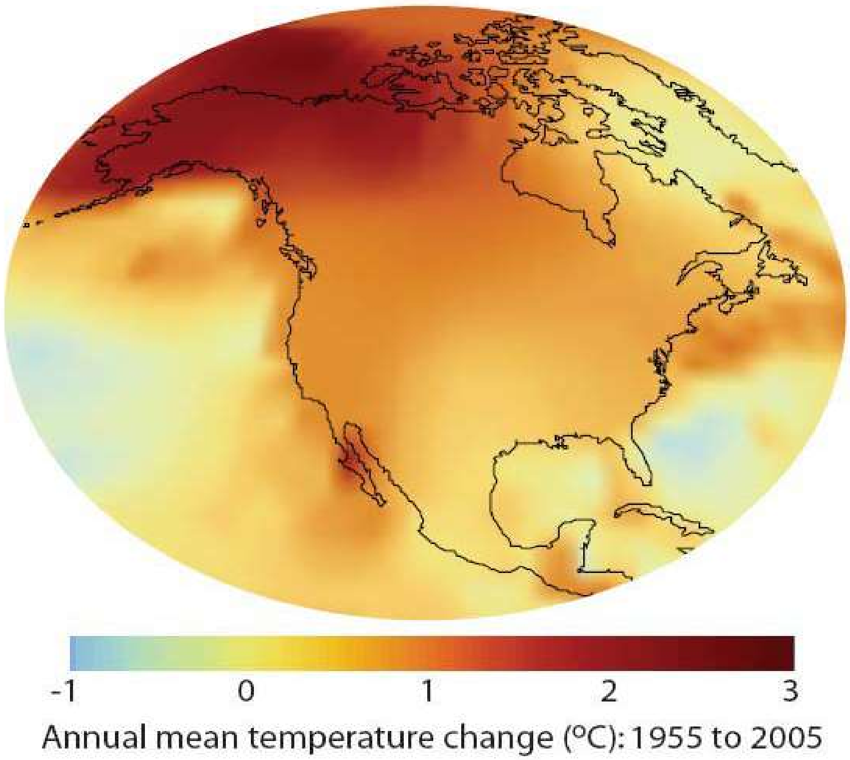


FIGURE 3 Temperature trends in North America, 1955 to 2005. The darker areas have experienced greater changes in temperature. For example, the Pacific Northwest had average temperatures about 1°C higher in 2005 than in 1955, while Alaska's average temperature had risen by over 2°C. SOURCE: Created with data from Goddard Institute for Space Studies.

Sea levels are rising

Climate change also means that sea levels are rising. Not only do warmer temperatures cause glaciers and land ice to melt (adding more volume to oceans), but seawater also expands in volume as it warms. The global average sea level rose by 1.7 mm/yr (0.07in/yr) during the 20th century, but since satellite measurements began in 1992, the rate has been 3.1 mm/year (0.12in/yr)(IPCC 2007a). Along some parts of the U.S. coast, tide gauge records show that sea level rose even faster (up to 10 mm/yr, 0.39in/yr) because the land is also subsiding. As sea level rises, shoreline retreat has been taking place along most of the nation's sandy or muddy shorelines, and substantial coastal wetlands have been lost due to the combined effects of sea-level rise and direct human activities. In Louisiana alone, 4900 km^2 (1900 mi^2) of wetlands have been lost since 1900 as a result of high rates of relative sea-level rise together with curtailment of the supply of riverborne sediments needed to build wetland soils. The loss of these wetlands has diminished the ability of that region to provide many ecosystem services, including commercial fisheries, recreational hunting and fishing, and habitats for rare, threatened, and migratory species, as well as weakening the region's capacity to absorb storm surges like those caused by Hurricane Katrina (Day et al. 2007). Higher sea levels can also change the salinity and water circulation patterns of coastal estuaries and bays, with varying consequences for the mix of species that can thrive there.

Other effects are being seen

Water Cycle

Climate change is linked to a number of other changes that already can be seen around the world. These include earlier spring snowmelt and peak stream flow, melting mountain glaciers, a dramatic decrease in sea ice during the arctic summer, and increasing frequency of extreme weather events, including the most intense hurricanes (IPCC 2007b). Changes in average annual precipitation have varied from place to place in the United States (Figure 4).

Climate dynamics and the cycling of water between land, rivers and lakes, and clouds and oceans are closely connected. Climate change to date has produced complicated effects on water balances, supply, demand, and quality. When winter precipitation falls as rain instead of snow and as mountain snowpacks melt earlier, less water is "stored" in the form of snow for slow release throughout the summer (Mote 2003), when it is needed by the wildlife in and around streams and rivers and for agriculture and domestic uses. Even if the amount of precipitation does not change, warmer temperatures mean that moisture evaporates more quickly, so that the amount of moisture available to plants declines. The complex interaction between temperature and water demand and availability means that climate change can have many different kinds of effects on ecosystems.

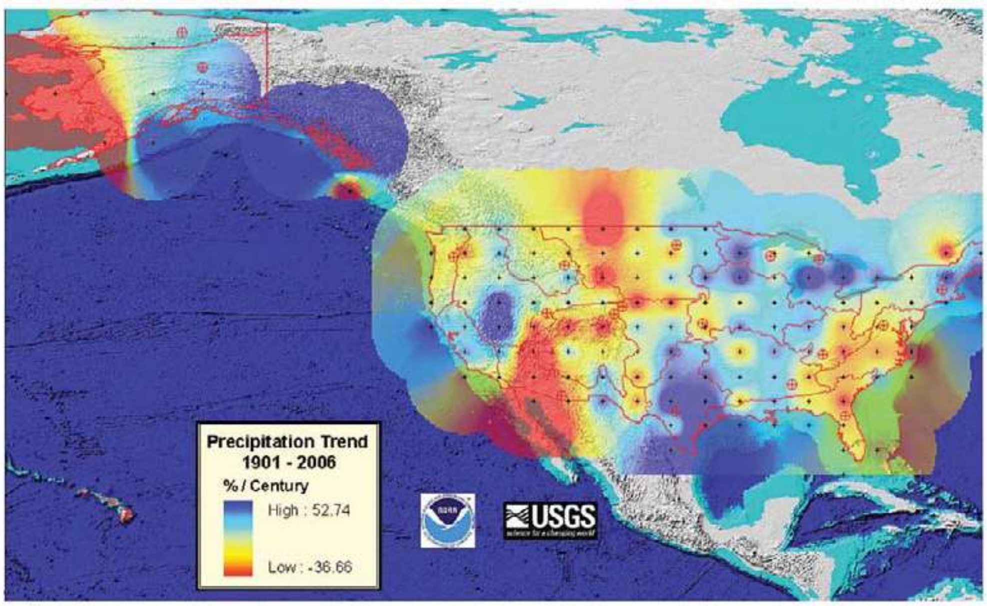


FIGURE 4 Trends in precipitation from 1901 to 2006 in the United States. Areas in red are averaging some 30 percent less precipitation per year now than they received early in the 1900s. Dark blue areas are averaging 50 percent more precipitation per year. SOURCE: Backlund 2008. Created with data from the USGS and NOAA/NCDC.

Extreme Events

The character of extreme weather and climate events is also changing on a global scale. The number of frost days in midlatitude regions is decreasing, while the number of days with extreme warm temperatures is increasing. Many land regions have experienced an increase in days with very heavy rain, but the recent CCSP report on climate extremes concluded that "there are recent regional tendencies toward more severe droughts in the southwestern U.S., parts of Canada and Alaska, and Mexico" (Kunkel et al. 2008, Dai et al. 2004; Seager et al., 2007).

These seemingly contradictory changes are consistent with a climate in which a greater input of heat energy is leading to a more active water cycle. In addition, warmer ocean temperatures are associated with the recent increase in the fraction of hurricanes that grow to the most destructive categories 4 and 5 (Emanuel 2005; Webster et al. 2005).

Arctic Sea Ice

Every year the area covered by sea ice in the Arctic Ocean expands in the winter and contracts in the summer. In the first half of the 20th century the annual minimum sea-ice area in the Arctic was usually in the range of 10 to 11 million km^2 (3.86 to 4.25 million mi^2) (ACIA 2005). In September 2007 sea-ice area hit a single-day minimum of 4.1 million km^2 (1.64 million mi^2), a loss of about half since the 1950s (Serreze et al. 2007). The decrease in area is matched by a dramatic decrease in thickness. From 1975 to 2000 the average thickness of Arctic sea ice decreased by 33 percent, from 3.7 to 2.5 m (12.3 to 8.3 ft) (Rothrock et al. 2008).

Ocean Acidification

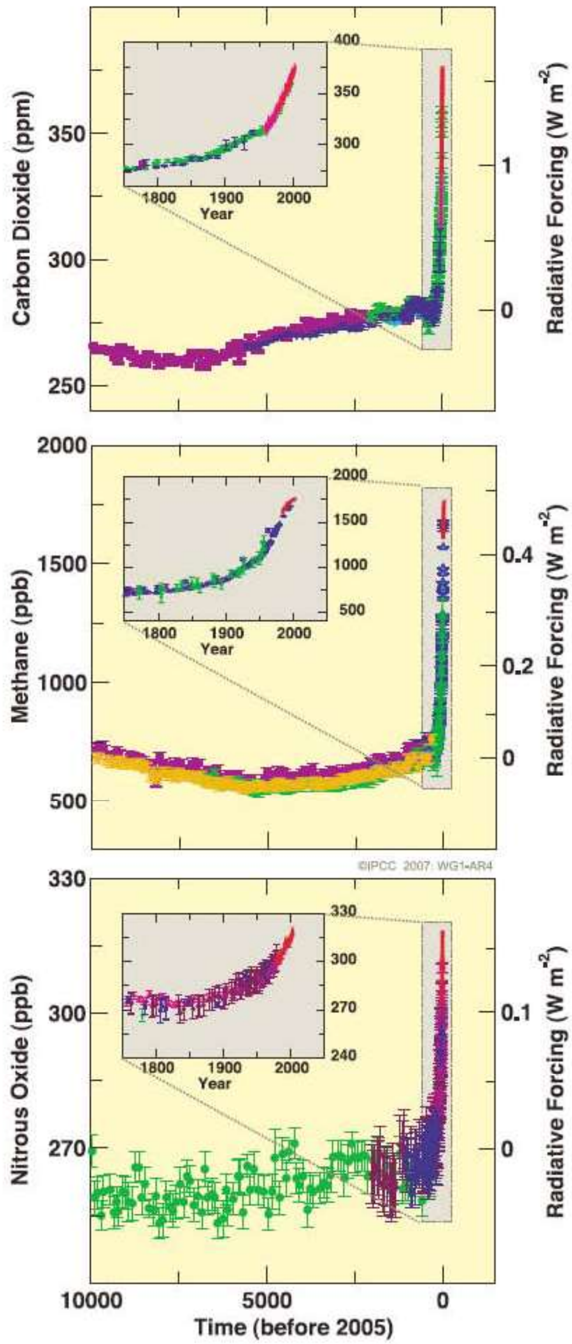
About one-third of the carbon dioxide emitted by human activity has already been taken up by the oceans, thus moderating the increase of carbon dioxide concentration in the atmosphere and global warming. But, as the carbon dioxide dissolves in sea water, carbonic acid is formed, which has the effect of acidifying, or lowering the pH, of the ocean (Orr et al. 2005). Although not caused by warming, acidification is a result of the increase of carbon dioxide, the same major greenhouse gas that causes warming. Ocean acidification has many impacts on marine ecosystems. To date, laboratory experiments have shown that although ocean acidification may be beneficial to a few species, it will likely be highly detrimental to a substantial number of species ranging from corals to lobsters and from sea urchins to mollusks (Raven et al. 2005; Doney et al. 2008; Fabry et al. 2008).

Causes of climate change

Both natural variability and human activities are contributing to observed global and regional warming, and both will contribute to future climate trends. It is very likely that most of the observed warming for the last 50 years has been due to the increase in greenhouse gases related to human activities (in IPCC reports, "very likely" specifically means that scientists believe the statement is at least 90 percent likely to be true; "likely" specifically means about two-thirds to 90 percent likely to be true [IPCC 2007b]). While debate over details is an important part of the scientific process, the climate science community is virtually unanimous on this conclusion.

The physical processes that cause climate change are scientifically well documented. The basic physics of the way greenhouse gases warm the climate were well established by Tyndall, Ahrrenius, and others in the 19th century (Bolin 2007). The conclusions that human actions have very likely caused most of the recent warming and will likely cause more in the future are based on the vast preponderance of accumulated scientific evidence from many different kinds of observations (IPCC 2007b). Since the beginning of the Industrial Revolution, human activities that clear land or burn fossil fuels have been injecting rapidly increasing amounts of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) into the atmosphere. In 2006 emissions of CO_2 were about 36 billion metric tons (39.6 billion English tons), or about 5.5 metric tons (6.0 English tons) for every human being (Raupach et al. 2007). In the United States average CO_2

emissions in 2006 were approximately 55 kg (120 lb) per person per day. As a consequence of these emissions, atmospheric CO_2 has increased by about 35 percent since 1850. Scientists know that the increases in carbon dioxide in the atmosphere are due to human activities, not natural processes, because they can fingerprint carbon dioxide (for example, by the mix of carbon isotopes it contains, its spatial pattern, and trends in concentration over time) and identify the sources. Concentrations of other greenhouse gases have also increased, some even more than CO_2 in percentage terms (Figure 5). Methane, which is 25 times more effective per molecule at trapping heat than CO_2, has increased by 150 percent. Nitrous oxide (N_2O), which is nearly 300 times more effective per molecule than CO_2 at trapping heat, has increased by over 20 percent (Prinn et al. 2000; Flückiger et al. 2002). Scientific knowledge of climate is far from complete. 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. These uncertainties, however, concern the details and not the core mechanisms that give scientists high confidence in their basic conclusions.



Atmospheric concentrations of CO_2, CH_4 and N_2O over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colors for different studies) and atmospheric samples (red lines). The corresponding radiative forcings (amount of energy trapped per unit area) relative to 1750 are shown on the right hand axes of the large panels. Source: IPCC 2007d.

FIGURE 5: Historical concentrations of greenhouse gasses CO_2, CH_4, and N_2O over the past 10,000 years. For each of these greenhouse gases, the characteristic "hockey stick" shape of the

curve is the result of large increases in the concentrations of these gases very recently, compared to their relatively stable levels over the past 10,000 years. SOURCE: IPCC 2007d.

What do we expect from future climate change?

Evidence of rising atmospheric and ocean temperatures, changing precipitation patterns, rising sea levels, and decreasing sea ice is already clear. Average temperatures will almost certainly be warmer in the future. The amount of future climate change depends on human actions. A large number of experiments with climate models indicate that if the world continues to emphasize rapid economic development powered by fossil fuels, it will probably experience dramatic warming during the 21st century. For this kind of "business as usual" future the IPCC (IPCC 2007b) projects a likely range of global warming over 1990 levels of 2.4-6.4ºC (4.3-11.5ºF) by 2100 (Figure 6, scenario A1F1). If greenhouse gas emissions grow more slowly, peak around the year 2050, and then fall, scientists project a likely warming over 1990 levels of 1.1-2.9ºC (2.0-5.2ºF) by 2100 (Figure 6, scenario B1).[5]

Temperature increases at the high end of the range of possibilities are very likely to exceed many climate thresholds. Warming of 6°C (10.8°F) or more (the upper end of the projections that the 2007 IPCC rates as "likely") would probably have catastrophic consequences for lifestyles, ecosystems, agriculture, and other livelihoods, especially in the regions and populations with the least resources to invest in adaptation—that is, the strategies and infrastructure for coping with the climate changes. Warming to the high end of the range would also entail a global average rate of temperature change that, for the next century or two, would dramatically exceed the average rates of the last 20,000 years, and possibly much further into the past.

Mean seawater temperatures in some U.S. coastal regions have increased by as much as 1.1°C (2°F) during the last half of the 20th century and, based on IPCC model projections of air temperature, are likely to increase by as much as 2.2-4.4°C (4-8°F) during the present century. "Business as usual" emissions through 2100 would likely lead to oceans with surface temperatures that are 2-4ºC (3.6-7.2ºF) higher than now and surface waters so acidified that only a few isolated locations would support the growth of corals (Cao et al. 2007). Most marine animals, especially sedentary ones, and plants are expected to be significantly stressed by these changes (Hoegh-Guldberg et al. 2007). Some may be able to cope with either increased temperatures or more acidic waters, but adjusting to both may not be feasible for many species.

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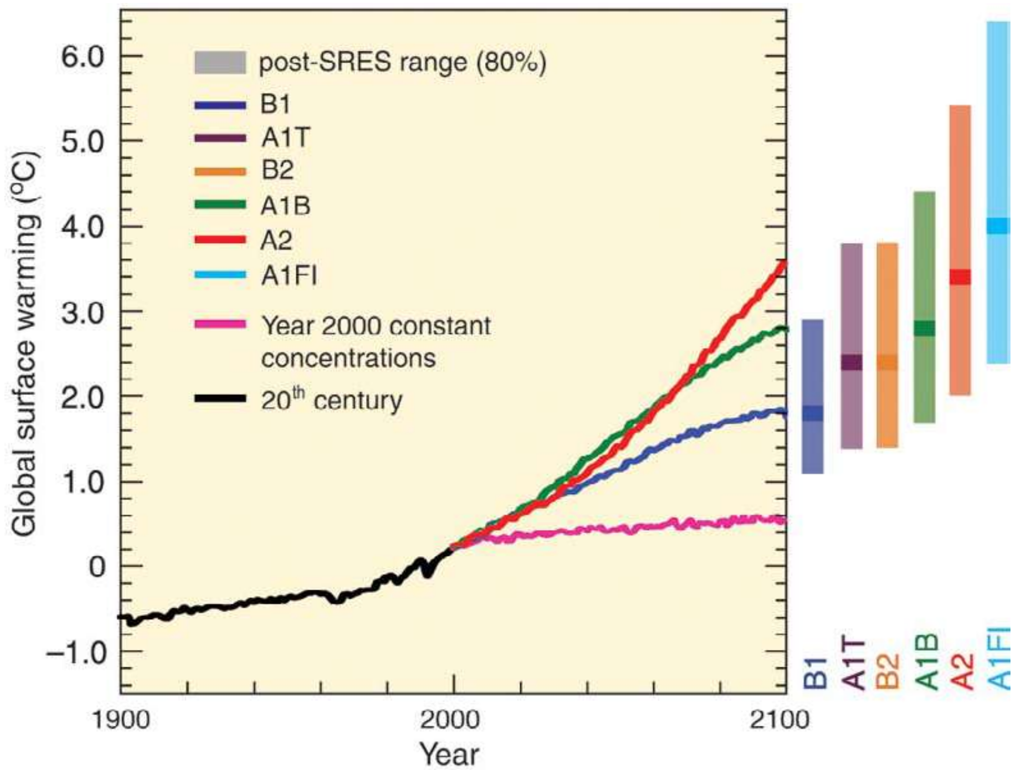
[5] Projections of warming are given as a range of temperatures for three reasons. First, gaps in the scientific understanding of climate limit the accuracy of projections for any specific concentration of greenhouse gases. Changes in wind and clouds can increase or decrease the warming that occurs in response to an increase in the concentration of greenhouse gases. Loss of ice on the sea or snow on land increases the amount of the incoming sunlight that is absorbed, amplifying the warming from greenhouse gases. Second, the pattern of future emissions and the mix of compounds released to the atmosphere cannot be predicted with high confidence. Some kinds of compounds that produce warming remain in the atmosphere only a few days (Ramanathan et al. 2007). Others, like CO_2, remain for centuries and longer (Matthews and Caldeira 2008). Still other compounds tend to produce aerosols or tiny droplets or particles that reflect sunlight, cooling the climate. Third, there is substantial uncertainty about the future role of the oceans and ecosystems on land. In the past, oceans and land ecosystems have stored, at least temporarily, about half of the carbon emitted to the atmosphere by human actions. If the rate of storage increases, atmospheric CO_2 will rise more slowly. If it decreases, then atmospheric CO_2 will rise more rapidly (Field et al. 2007).

Continued emissions under the "business as usual" scenario could lead by 2100 to 0.6 m (2 ft) or more of sea-level rise. Continuation of recent increases in loss of the ice caps that cover Greenland and West Antarctica could eventually escalate the rate of sea-level rise by a factor of 2 (Overpeck et al. 2006; Meehl et al. 2007; Alley et al. 2005; Gregory and Huybrechts 2006; Rahmstorf 2007).

There will also be hotter extreme temperatures and fewer extreme cold events. An increase in climate variability, projected in some models, will entail more frequent conditions of extreme heat, drought, and heavy precipitation. A warmer world will experience more precipitation at the global scale, but the changes will not be the same everywhere. In general, the projections indicate that dry areas, especially in the latitude band just outside the tropics (for example, the southwestern United States), will tend to get drier on average (IPCC 2007b; Kunkel et al. 2008). Areas that are already wet, especially in the tropics and closer to the poles, will tend to get wetter on average. Increased climate variability and increased evaporation in a warmer world could both increase the risk and likely intensity of future droughts.

Changes in the frequency or intensity of El Niño events forecast by climate models are not consistent (IPCC 2007b). El Niños are important because they are often associated with large-scale drought and floods in the tropics and heavy rains just outside the tropics, but projecting how the interaction between climate change and El Niño events will affect precipitation patterns is difficult. Another example of inconsistent results from models is that model simulations indicate that future hurricane frequency and average intensity could either increase or decrease (Emanuel et al. 2008), but it is likely that rainfall and top wind speeds in general will increase in a world of warmed ocean temperatures.

For all of these different factors—temperature, precipitation patterns, sea-level rise and extreme events—both the magnitude and speed of change are important. For both ecosystems and human activities, a rapid *rate* of climate change presents challenges that are different from, but no less serious than, the challenges from a large *amount* of change (Schneider and Root 2001).



Solid lines are multi-model global averages of surface warming for scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The pink line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099. All temperatures are relative to the period 1980-1999. SOURCE IPCC 2007b.

FIGURE 6 Projected future temperatures. This figure shows projected trends of average global surface temperature, based on output from all of the major climate models, shown as continuations of the 20th century observations (with the average for 1980-1999 plotted as 0). The pink line represents what would happen if CO_2 concentrations could be held constant at year 2000 levels. Scenarios B1, A1B and A2 represent alternative possible futures. A1B and B1 are futures with modest population growth, rapid economic growth, and a globally integrated economy, with A1B focusing on manufacturing and B1 focusing on service industries. A2 is a world with more rapid population growth but slower economic growth and less economic integration. The bars to the right of the graph represent the likely range of average global temperature from the same models in the years 2090-2099 for a wider range of possible futures, with the horizontal bar in the middle indicating the average across the models. As of 2006, actual CO_2 emissions were higher than those in the A2 scenario, making the full range of scenarios look like underestimates, at least for the first years of the 21st century. (IPCC 2007b, Raupach et al. 2007).

Climate change can impact ecosystems in many ways

Hundreds of studies have documented responses of ecosystems, plants, and animals to the climate changes that have already occurred (Parmesan 2006; Rosenzweig et al. 2007). These studies demonstrate many direct and indirect effects of climate change on ecosystems. Changes in temperature, for example, have been shown to affect ecosystems directly: the date when some plants bloom is occurring earlier in response to warmer temperatures and earlier springs. Extreme temperatures, both hot and cold, can be important causes of mortality, and small changes in extremes can sometimes determine whether a plant or animal survives and reproduces in a given location.

Changes in temperature, especially when combined with changes in precipitation, can have indirect effects as well. For many plants and animals soil moisture is critically important for many life processes; changes in precipitation and in the rate of evaporation interact to determine whether moisture levels remain at a level suitable for various organisms. For fish and other aquatic organisms both water temperature and water flow are important and influenced by the combined effects of altered air temperatures and precipitation. For example, warmer, drier years in the northwestern United States, often associated with El Niño events and anticipated to be more common under many climate scenarios, have historically been associated with below-average snowpack, stream flow, and salmon survival (Mote 2003). Some salmon populations are especially sensitive to summer temperatures; others are sensitive to low stream-flow volumes in the fall (Crozier and Zabel 2006). The fact that climate change leads to rising seas means that organisms and ecosystems located in coastal zones between the ocean and terrestrial habitats are squeezed, especially when the coastal land is occupied by buildings or crops.

The ecological impacts of climate change are not inherently beneficial or detrimental for an ecosystem. 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 state prior to human-caused climate change. Measured by particular ecosystem services, some changes could be beneficial; for example, warmer temperatures extend the growing season in some latitudes, and higher CO_2 levels increase the growth of some land plants, with higher potential yields of food and forestry products (Nemani et al. 2003). Others are detrimental, for example, western mountain areas with a longer snow-free season are experiencing increased wildfires, reduced potential wood harvests, and loss of some recreational opportunities (Westerling et al. 2006). In some settings uncertainty about future ecosystem services may be a cost in itself, motivating investments that may not turn out to be necessary or that may be insufficient to effectively address changing needs. To date, many species have responded to the effects of climate change by extending their range boundaries both toward the poles (for example, northward in the U.S.) and up in elevation, and by shifting the timing of spring and autumn events. Plants and animals needing to move but prevented from doing so, for example, because appropriate habitat is not present at higher elevations, are at greater risk of extinction. Shifting species ranges, changes in the timing of biological events, and a greater risk of extinction all affect the ability of ecosystems to provide the critical services—products, regulation of the environment, enhanced human quality of life, and natural infrastructure—they have been providing.

Ecosystems can adjust to change—over time

Ecosystems are not static. They are collections of living organisms that grow and interact and die. Ecosystems encounter an ever changing landscape of weather conditions and various kinds of disturbances, both subtle and severe. Whatever conditions an ecosystem encounters, the individual organisms and species react to the changes in different ways. Ecosystems themselves do not move, individuals and species do; some species can move farther and faster than others, but some may not be able to move at all. For example, a long-lived tree species may take decades to spread to a new range, while an insect with many hatches per year could move quickly. A species that already lives on mountaintops may have nowhere else to retreat. Rapid and extreme disturbances can have major and long-lasting ecological impacts. For example, a severe drought, wildfire, or hurricane can fundamentally reshape an area, often for many decades. In one of the most dramatic examples the impact of an asteroid 65 million years ago is believed to have so radically changed conditions on Earth that the dominant animals, the dinosaurs, died off and were supplanted by mammals (Alvarez et al. 1990).

On longer time scales, most places on Earth have experienced substantial climate changes. During the peak of the last ice age, approximately 21,000 years ago, most of Canada and the northern United States were under thousands of feet of ice (Jansen et al. 2007). Arctic vegetation thrived in Kentucky, and sea levels were about 120 m (400 ft) lower than at present. Over the past million years Earth has experienced a series of ice ages, separated by warmer conditions. Global average temperatures during these ice ages were about 4-7°C (7.2-12.6°F) cooler than present, with the cooling and warming occurring over many thousands of years (Jansen et al. 2007). These ice ages triggered extensive ecological responses, including large shifts in the distributions of plants and animals, as well as extinctions. The massive changes during past ice ages certainly pushed ecosystems off large swaths of Earth's surface as ice-dominated landscapes advanced. However, these changes were generally slow enough that surviving species could move and reassemble into novel, as well as familiar-looking, ecosystems as the ice retreated (Pitelka et al. 1997; Overpeck et al. 2003). The 10,000 years since the last ice age have seen substantial regional and local climate variation, but on a global scale climate was relatively stable, and these regional climate changes did not drive species to extinction nor result in the scale of global ecosystem change seen during glacial-to-interglacial transitions. Even when the global climate is not changing noticeably, regional climate variability (droughts, storms, and heat waves) can have dramatic regional (often short-term) impacts. In a period of climate change it is important to remember that this climate variability will continue to occur on top of the more long-term human-caused climate changes.

Data on ecosystem responses to disturbances in the distant past can provide valuable information about likely responses to current and future climate change. But it is important to recognize that the current rate of increase of CO_2 in Earth's atmosphere is faster than at any time measured in the past, indicating that human-caused global climate change in the current era is likely to be exceedingly rapid, many times faster than the long-term global changes associated with onset and termination of the ice ages (Jansen et al. 2007). One of the big concerns about the future is that climate changes in some places may be too fast for organisms to respond in the ways that have helped sustain ecosystem services in response to natural changes in the past. Understanding how quickly ecosystems can and cannot adjust is one of the key challenges in climate change research.

Climate change, other stresses, and the limits of ecosystem resilience

Climate change is not the only way humans are affecting ecosystems. Humans have a large and pervasive influence on the planet. We use a substantial portion of the land for agriculture and the oceans for fishing (Worm et al. 2006; Ellis and Ramankutty 2008). Many rivers are dammed to provide water for crops or people, or they are polluted with fertilizer or other chemicals. Chemical residues and the by-products of industrial activity, from acid precipitation to ozone, affect plant growth. Human activities, especially land and ocean use, limit some opportunities for species migrations while opening routes for other species. Globally humans have moved many non-native species from one ecosystem to another. Ecosystems operate in a context of multiple human influences and interacting factors.

Earth's ecosystems are generally resilient to some range of changes in climate. A resilient ecosystem is one that can withstand a stress like pollution or rebuild after a major disturbance like a serious storm. A resilient ecosystem can cope with a drought or an unusually hot summer in ways that alter some aspects of ecosystem function but do not lead to a major shift in the type of ecosystem or the services it provides. Thus, a resilient ecosystem may not appear to be affected by modest or slow climate changes. But this resilience has limits. When a change exceeds those limits, or is coupled with other simultaneous changes that cause stress, the ecosystem undergoes a major change, often shifting to a fundamentally different ecosystem type. There is a threshold point when dramatic ecosystem transformations may occur (Gunderson and Pritchard 2002). These thresholds are like the top of a levee as the water level rises. As long as the water level is even slightly below the top of the levee, function is normal. But once it rises above the levee, there is a flood. This kind of threshold response is common in ecosystems, where extreme events like heat waves often serve as triggers for an irreversible transition of the ecosystem to a new state.

Currently plants and animals are responding to rapid climate change while simultaneously coping with other human-created stresses such as habitat loss and fragmentation due to development, pollution, invasive species, and overharvesting. How do we know climate change itself is causing major changes in ecosystems? First, species changing their ranges in the Northern Hemisphere are almost uniformly moving their ranges northward and up in elevation in search of cooler temperatures (Parmesan and Yohe 2003; Parmesan 2006; Rosenzweig et al. 2007). If any or all of the other stressors were the major cause of ecosystem changes, plants and animals would move in many directions in addition to north, and to lower as well as higher elevations. Second, when we look at the association over time of changes between species ranges and temperatures modeled using only natural variation in climate, such as sunspots and volcanic dust in the stratosphere, the relationship is poor. When temperatures are modeled using natural variability as well as human-caused drivers, such as emission of CO_2 and methane, the association is very strong. Consequently, humans are very likely causing changes in regional temperatures to which in turn the plants and animals are responding (Root et al. 2005).

Documented Current Ecological Impacts of Climate Change

Given the compounding factors discussed in the preceding section, it is generally difficult to attribute ecological changes directly or solely to the effects of climate change. Evidence of the ecological impacts of climate change becomes more convincing when trends are observed among hundreds of species rather than relying on studies of a few particular species. Two widely documented and well-studied general ecological impacts of climate change that provide a glimpse into the broader issue are climate-induced shifts in species' ranges and seasonal shifts in biological activities (known as phenology) or events. These types of change have been observed in many species, in many regions, and over long periods of time.

Range and seasonal shifts are not the only general impacts of climate change; other impacts that affect many ecosystems are changes in growth rates, the relative abundance of different species, processes like water and nutrient cycling, and the risk of disturbance from fire, insects, and invasive species.

Range shifts

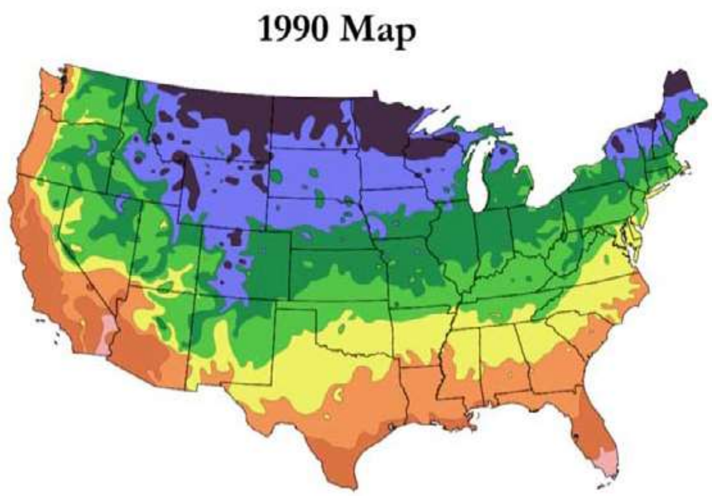
Climate change is driving the most massive relocation of species to occur without direct human assistance since the beginning of the current interglacial (warm) period (Parmesan 2006). Each species has a range of climates within which it can survive and reproduce. Species can live only in geographic areas where they can tolerate local temperatures, rainfall, and snowfall (see Figure 7). As Earth warms, the tolerable climate ranges for many species are shifting their locations. About 40 percent of wild plants and animals on land that have been followed over decades are relocating in order to remain within suitable climate conditions (Parmesan and Yohe 2003). Maximum range shifts observed during the past 30 years (up to 1000 km poleward and 400 m upward shifts) surpass responses to regional climate variability during the current interglacial (warm) period of the past 10,000 years, and are approaching the magnitudes of range shifts which occurred during the transition from the last glacial maximum to the current interglacial (Coope 1994,1995; Davis and Shaw 2001; Parmesan 2006; Seimon et al. 2007).

Populations or entire species that are unable to move become stressed as the climate around them becomes unsuitable, and ultimately are at high risk of extinction if they cannot relocate (Williams et al. 2003; Thomas et al. 2004; Bomhard et al. 2005; Thuiller et al. 2005; Fischlin et al. 2007). For example, several U.S. Fish and Wildlife Service-listed endangered species live on only one or a few mountaintops. When such a restricted species distribution is coupled with poor dispersal abilities, these species are unlikely to be able to colonize new habitats as their current locations become climatically unsuitable..

One obvious consequence of shifting species ranges is that many of the nature preserves, parks, refuges, and marine protected areas may no longer experience the climates required by the very species for which they were founded. In another hundred years the nation's carefully planned park, preserve, and refuge system may not function as intended (Opdam and Waschler 2004). The movement of species out of the borders of nature preserves is compounded by the fact that some of the preserved areas are also the ones being hardest hit by climate change. For example, the harsh but fragile landscapes of the boreal tundra on the high peaks of the Grand Tetons, the High Sierra, and the Alaska Range, are being strongly affected by human-caused climate change.

Range shifts acutely affect species in the Arctic and Antarctic. Temperatures are rising more rapidly near the poles—up to 3°C (5.4°F) warming since 1850 (compared with 0.75°C [1.3°F] average global increase) (IPCC 2007b). As sea ice gets thinner and shrinks in area, so too shrink animal populations that use ice as their home, including the polar bear and the ringed seal in the Arctic (Stirling et al. 1999; Derocher et al. 2004; Ferguson et al. 2005). In the Antarctic, declines in Adelié penguin populations reflect warming-induced declines in sea ice and warming-induced increases in precipitation (Croxall et al. 2002; Ducklow et al. 2007). These animals are retreating toward the poles, and are rapidly reaching the end of Earth as they know it.

Cold-adapted species living at the tops of mountains are also being stranded with nowhere to move as warmer temperatures—and formerly lower-elevation species—creep up to higher elevations. As these formerly lower-elevation species move into conditions suitable at higher elevations the available land area tends to get smaller as the elevation gets higher (Figure 8). Of course, an upward shift in each forest type means that the next higher type is either eliminated or pushed even higher. The tundra and subalpine plants and animals that grace the tops of the many high peaks and ridges may disappear completely as they are effectively pushed off the tops of the mountains.



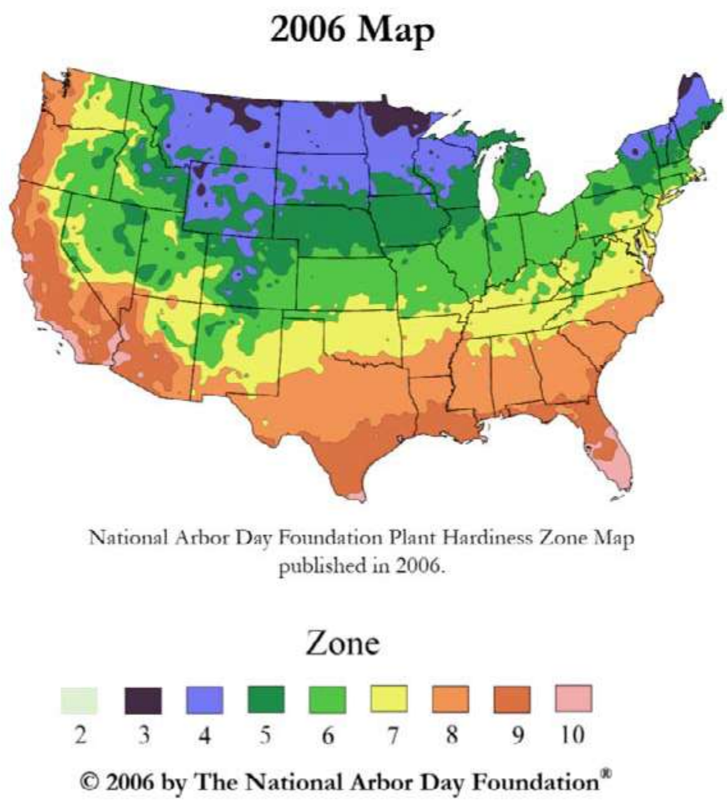


FIGURE 7 Shifts in plant hardiness zones between 1990 and 2006. Many gardeners rely on plant hardiness zones to determine which plants will grow in their region. Each type of plant will thrive only in certain zones. These zones have changed since the map was established. The hardiness zone is moving north in most areas. This means that a plant that once could be grown only in the south can now be grown successfully in areas that were not suitable 15 years ago. However, it also means that some plants can no longer survive where they were planted. SOURCE: The Arbor Day Foundation.

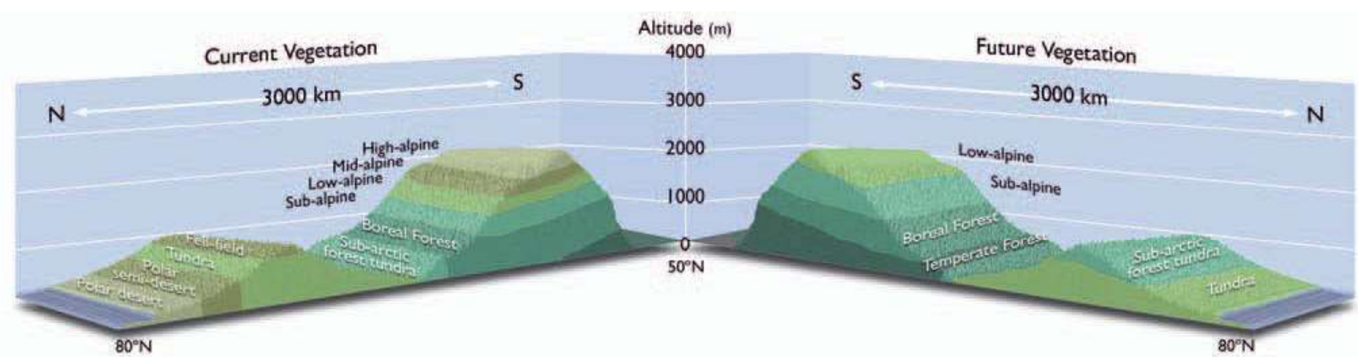


FIGURE 8 This figure shows current and future types of vegetation from north to south and from lower to higher elevation as a result of future warming. Each zone represents a type of ecosystem. In the future these zones move northward but also upward in altitude, replacing existing zones and creating new zones. At an elevation of 1000 m currently one sees subalpine vegetation in the south and fell-field in the north. In a warmer future, at 1000 m one would see

boreal forest in the south and subarctic forest in the north. This process is called range shift. SOURCE: ACIA 2004.

Seasonal Shifts

Climate change is also driving changes in phenology. Many biological events are timed based on seasonal cues, with most of the major ones occurring in the spring and autumn. Many studies looking at changes of the timing of spring events have found that over the last 30 to 40 years, various seasonal behaviors of numerous species now occur 15 to 20 days earlier than several decades ago (Parmesan and Yohe 2003; Root et al. 2003; Parmesan 2007). The types of changes include earlier arrival of migrant birds, earlier appearance of butterflies, and earlier flowering and budding of plants. For example, the date when buds open in the spring in aspen trees in Edmonton, Canada, shifted approximately 26 days earlier between 1900 and 2000, in response to a warming of nearly 2°C (Figure 9) (Beaubien and Freeland 2000). Lilacs carefully observed at over 1100 sites in North America expanded leaves and flowered an average of five to six days earlier in 1993 than in 1959. Autumn changes are not as obvious partly because species vary in the way that earlier springs affect their fall behavior. For example, some birds that arrive earlier in the spring also leave earlier in the fall, regardless of the weather. Many trees, on the other hand, respond to a later arrival of fall by delaying the date their leaves turn color.

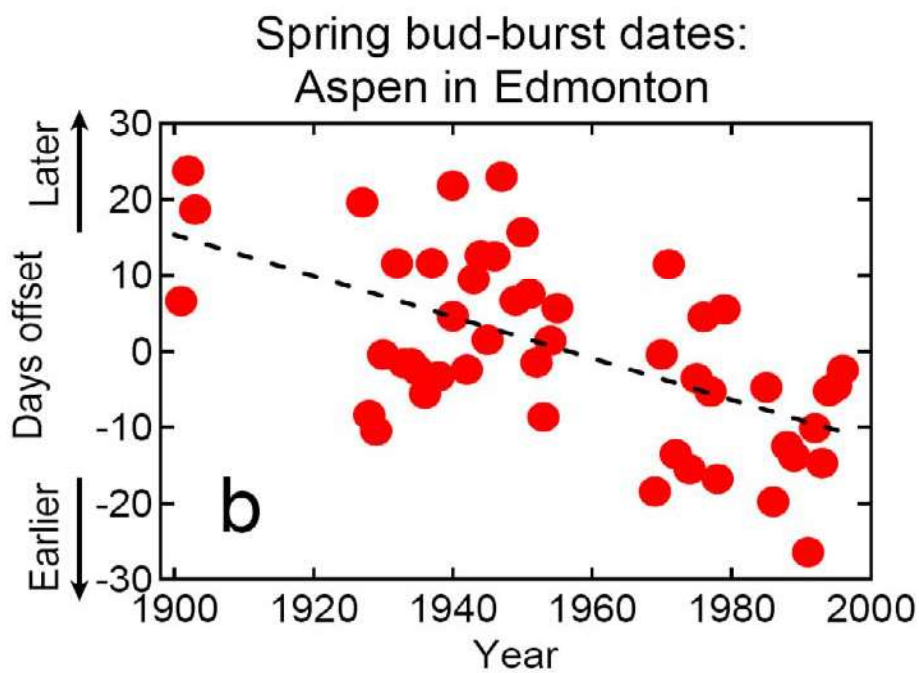


FIGURE 9 This graph shows when the buds on aspen trees opened in Edmonton, Canada during the 20th century. The zero point is the average date (for the entire century) when buds opened. Each circle represents an historical record of when buds opened in that particular year. The dotted line shows the trend; aspen buds are opening on average 25 days earlier than they did a century ago in response to warmer temperatures. The change in blooming date is an example of a seasonal, or phenology, shift. SOURCE: adapted from data in Beaubien and Freedland (2000).

If all the different species in an ecosystem shifted their spring behavior in exactly the same way, the impact of warming temperatures might be minimal. But what happens when a species depends upon another for survival (predator on prey, for example) and only one changes the timing of its spring activity? Such a change can disrupt the predator-prey interaction, which in turn can cause a drop in the predator population. For example, in Europe the bird known as the pied flycatcher has not changed the time it arrives on its breeding grounds, but the caterpillars it feeds its young are emerging earlier (Both et al. 2006). Missing the peak of food availability means fewer chicks are surviving and the pied flycatcher population is declining.

Another example of mismatched predator-prey emergence is seen in plankton blooms in the North Sea near England. There, many kinds of plankton (small marine organisms) have changed the timing of their major blooms, but not by the same amount. In response to a warming of about 0.9°C (1.6°F), *Ceratium fusus*, a tiny plant-like organism, shifted its peak bloom about a month earlier in 1981-2002, compared to 1958-1980, but copepods, their shrimp-like predators, shifted by only 10 days. This kind of mismatch appears to be common in the North Sea, with plants generally shifting farther than the animals that feed on them (Edwards and Richardson 2004).