OUR CHANGING CLIMATE

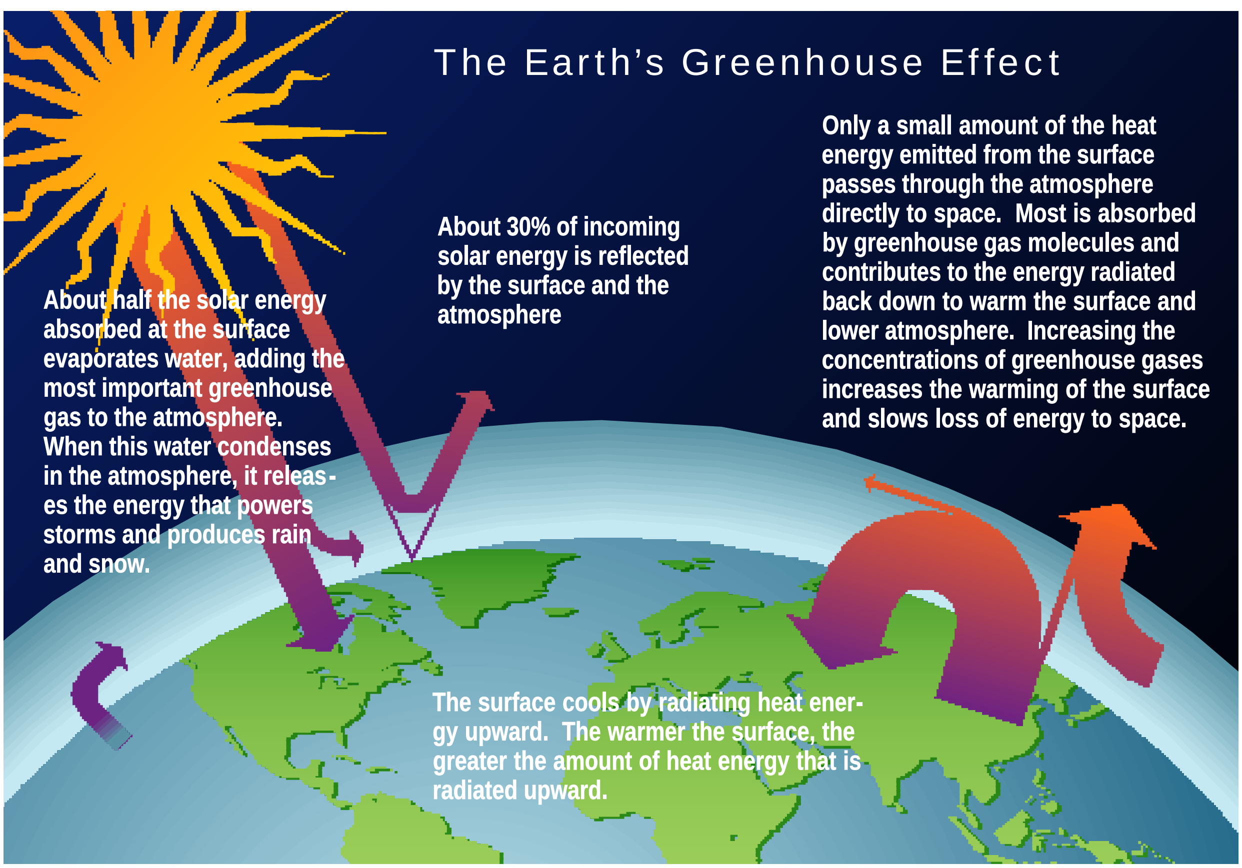
Global projections based on population growth and assumptions about energy use indicate that the CO_2 concentration will continue to rise, likely reaching somewhere between two and three times its pre-industrial level by 2100.

Climate and the Greenhouse Effect

Earth's climate is determined by complex interactions between the sun,oceans,atmosphere,land,and living things. The composition of the atmosphere is particularly important because certain gases (including water vapor, carbon dioxide,methane,halocarbons,ozone,and nitrous oxide) absorb heat radiated from the Earth's surface. As the atmosphere warms,it in turn radiates heat back to the surface,to create what is commonly called the "greenhouse effect." Changes in the composition of the atmosphere alter the intensity of the greenhouse effect. Such changes,which have occurred many times in the planet's history, have helped determine past climates and will affect the future climate as well.

Human Activities Alter the Balance

Humans are exerting a major and growing influence on some of the key factors that govern climate by changing the composition of the atmosphere and by modifying the land surface. The human impact on these factors is clear. The concentration of carbon dioxide (CO_2) has risen about 30% since the late 1800s. The concentration of CO_2 is now higher than it has been in at least the last 400,000 years. This increase has resulted from the burning of coal,oil,and natural gas,and the destruction of forests around the world to provide space for agriculture and other human activities. Rising concentrations of CO_2 and other greenhouse gases are intensifying Earth's natural greenhouse effect. Global projections of population growth and assumptions about energy use indicate that the CO_2 concentration will continue to rise,likely reaching between two and three times its late-19th-century level by 2100. This dramatic doubling or tripling will occur in the space of about 200 years,a brief moment in geological history.



The Climate Is Changing

As we add more CO_2 and other heat-trapping gases to the atmosphere,the world is becoming warmer (which changes other aspects of climate as well). Historical records of temperature and precipitation have been extensively analyzed in many scientific studies. These studies demonstrate that the global average surface temperature has increased by over 1ºF (0.6ºC) during the 20th century. About half this rise has occurred since the late 1970s. Seventeen of the eighteen warmest years in the 20th century occurred since 1980. In 1998,the global temperature set a new record by a wide margin, exceeding that of the previous record year, 1997, by about 0.3ºF (0.2ºC). Higher latitudes have warmed more than equatorial regions,and nighttime temperatures have risen more than daytime temperatures.

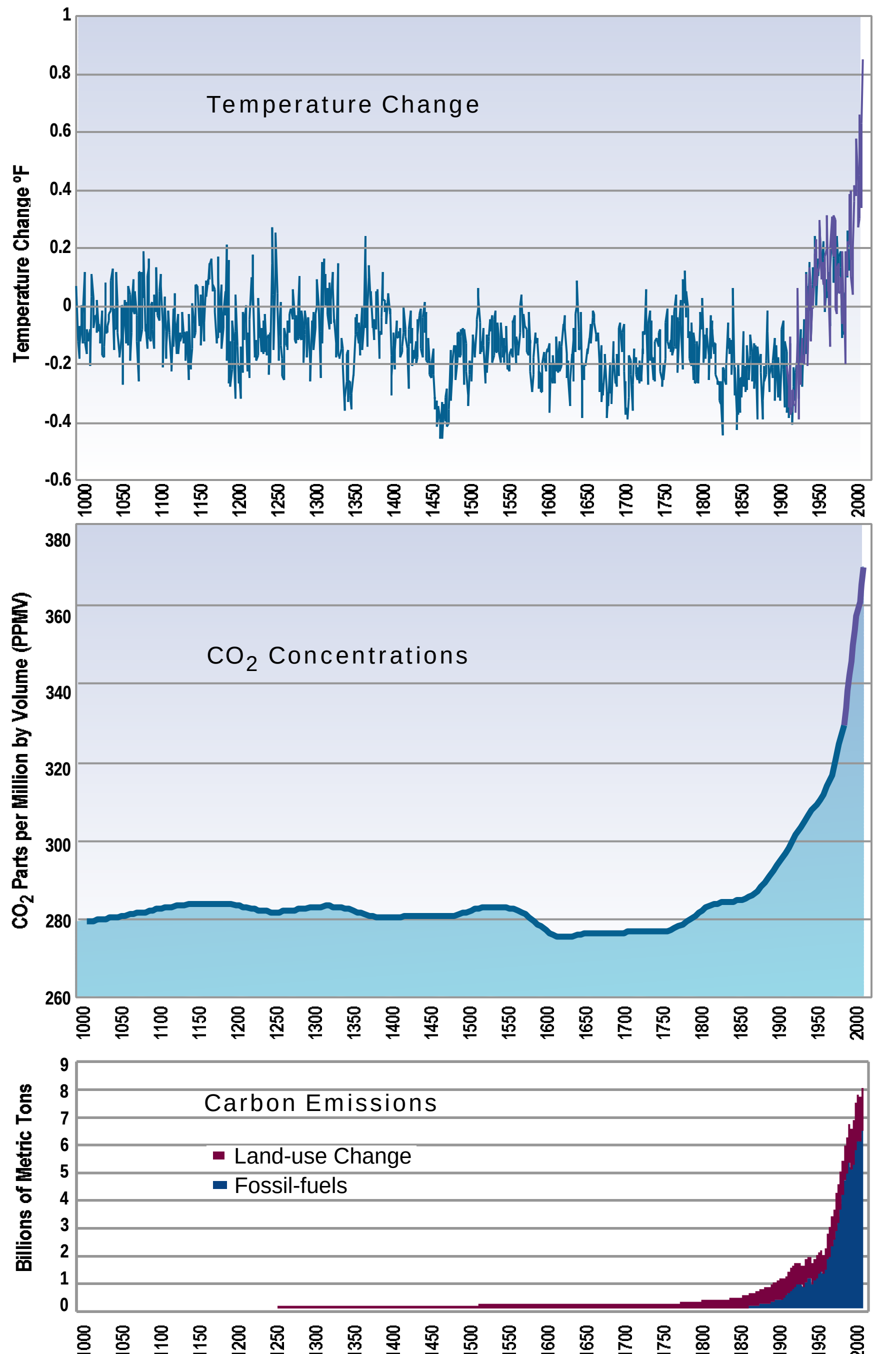
As the Earth warms,more water evaporates from the oceans and lakes, eventually to fall as rain or snow. During the 20th century, annual precipitation has increased about 10% in the mid- and high-latitudes. The warming is also causing permafrost to thaw, and is melting sea ice,snow cover, and mountain glaciers. Global sea level rose 4 to 8 inches (10-20 cm) during the 20th century because ocean water expands as it warms and because melting glaciers are adding water to the oceans.

According to the Intergovernmental Panel on Climate Change (IPCC),scientific evidence confirms that human activities are a discernible cause of a substantial part of the warming experienced over the 20th century. New studies indicate that temperatures in recent decades are higher than at any time in at least the past 1,000 years. It is very unlikely that these unusually high temperatures can be explained solely by natural climate variations.

The intensity and pattern of temperature changes within the atmosphere implicates human activities as a cause.

The relevant question is not whether the increase in greenhouse gases is contributing to warming,but rather, what will be the amount and rate of future warming and associated climate changes,and what impacts will those changes have on human and natural systems.

1000 Years of Global CO_2 and Temperature Change



Records of Northern Hemisphere surface temperatures, CO_2 concentrations, and carbon emissions show a close correlation. Temperature Change: **reconstruction of annual-average Northern Hemisphere surface air temperatures derived from historical records, tree rings, and corals (blue), and air temperatures directly measured (purple).** CO_2 Concentrations: **record of global CO_2 concentration for the last 1000 years, derived from measurements of CO_2 concentration in air bubbles in the layered ice cores drilled in Antarctica (blue line) and from atmospheric measurements since 1957.** Carbon Emissions: **reconstruction of past emissions of CO_2 as a result of land clearing and fossil fuel combustion since about 1750 (in billions of metric tons of carbon per year).**

TOOLS FOR ASSESSING CLIMATE CHANGE IMPACTS

For this study, three tools were used to examine the potential impacts of climate change on the US: historical records, comprehensive state-of-the-science climate simulation models, and sensitivity analyses designed to explore our vulnerability to future climate change. These three tools were used because prudent risk management requires consideration of a spectrum of possibilities.

Historical Records

How do changes in climate affect human and natural systems? Records from the past provide an informed perspective on this question. There have been a number of climate variations and changes during the 20th century. These include substantial warming, increases in precipitation, decade-long droughts, and reduction in snow cover extent. Analyzing these variations, and their effects on human and natural systems, provides important insights into how vulnerable we may be in the future.

Climate Model Simulations

Although Earth's climate is astoundingly complex, our ability to use supercomputers to simulate the climate is growing. Today's climate models are not infallible, but they are powerful tools for understanding what the climate might be like in the future.

A key advantage of climate models is that they are quantitative and grounded in scientific measurements. They are based on fundamental laws of physics and chemistry, and incorporate human and biological interactions. They allow examination of a range of possible futures that cannot be examined experimentally.

Our confidence in the accuracy of climate models is growing. The best models have been carefully evaluated by the IPCC and have the ability to replicate most aspects of past and present climates. Two of these models have been used to develop climate change scenarios for this Assessment. These scenarios should be regarded as projections of what might happen, rather than precise predictions of what will happen.

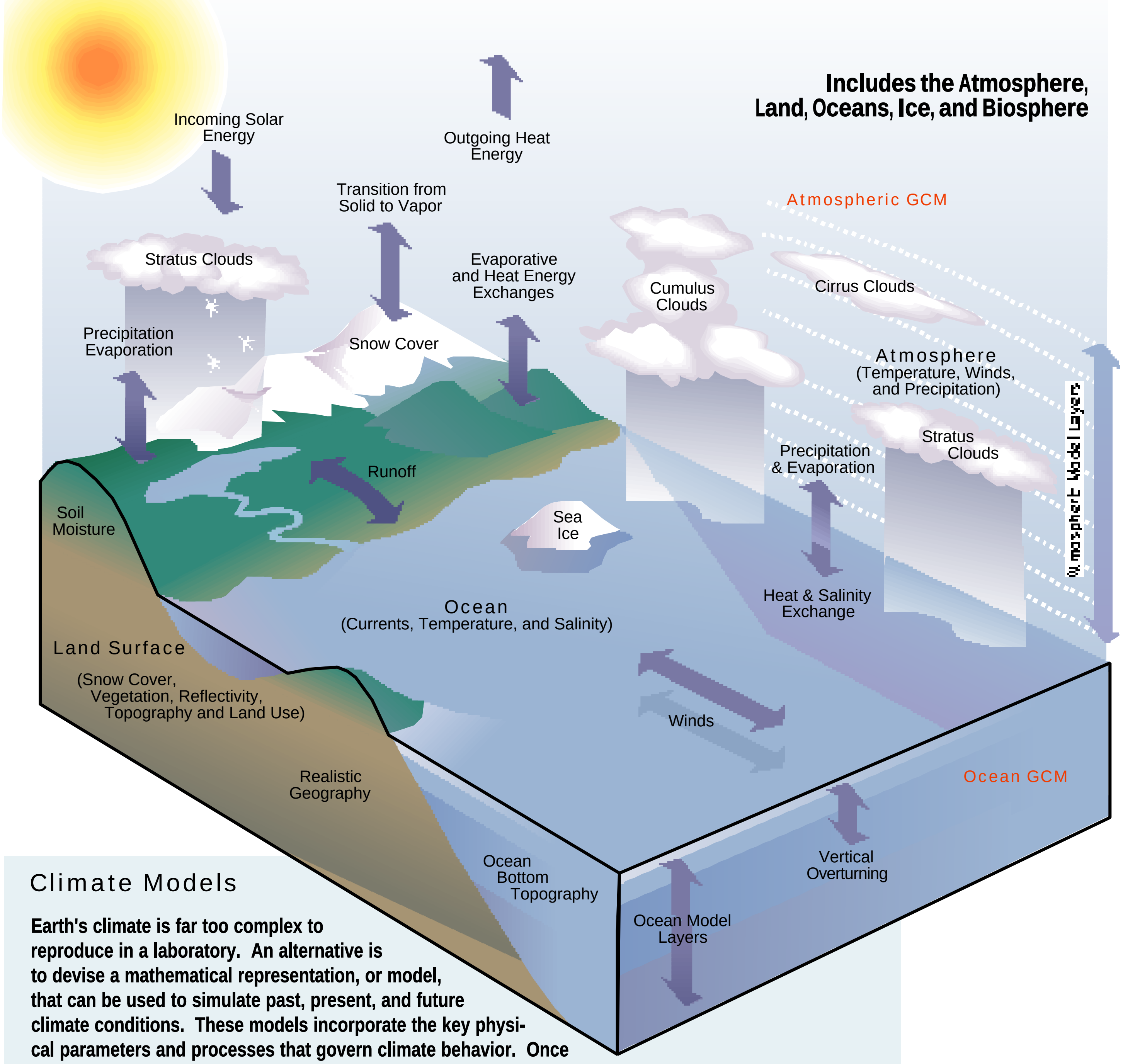
Sensitivity Analyses

What degree of climate change would cause significant impacts to natural and human systems? In other words, how vulnerable and adaptable are we? To help answer such questions, scientists can perform "sensitivity analyses" to determine under what conditions and to what degree a system is sensitive to change. Such analyses are not predictions that such changes will, in fact, occur; rather, they examine what the implications would be if the specified changes did occur. For example, an analyst might ask, "How large would climate change have to be in order to cause a specified impact?"

Climate Observations

Climatologists use two types of data to monitor climate change. The first are historical measurements of temperature, precipitation, humidity, pressure, and wind speed taken at thousands of locations across the globe. Because observing methods, instruments, and station locations have changed over time, climatologists use various methods to crosscheck and corroborate these historical data sets. For example, satellite and balloon records confirm that the planet has been warming for the past four decades, although rates of atmospheric and surface warming differ somewhat from decade to decade. To peer further back into the past, climatologists also analyze physical, biological, and chemical indicators. For example, past climate conditions can be inferred from the width of tree rings, air trapped in ancient ice cores, and sediment deposited at the bottom of lakes and oceans. Taken together, this information demonstrates that the Earth's climate over the past 10,000 years has been relatively stable compared to the 10,000 years that preceeded this period and compared to the 20th century.

Modeling the Climate System



Climate Models

Earth's climate is far too complex to reproduce in a laboratory. An alternative is to devise a mathematical representation, or model, that can be used to simulate past, present, and future climate conditions. These models incorporate the key physical parameters and processes that govern climate behavior. Once constructed, they can be used to investigate how a change in greenhouse gases, or a volcanic eruption, might modify the climate.

Computer models that simulate Earth's climate are called General Circulation Models or GCMs. The models can be used to simulate changes in temperature, rainfall, snow cover, winds, soil moisture, sea ice, and ocean circulation over the entire globe through the seasons and over periods of decades. However, mathematical models are obviously simplified versions of the real Earth that cannot capture its full complexity, especially at smaller geographic scales. Real uncertainties remain in the ability of models to simulate many aspects of the future climate. The models provide a view of future climate that is physically consistent and plausible, but incomplete. Nonetheless, through continual improvement over the last several decades, today's GCMs provide a state-of-the-science glimpse into the next century to help understand how climate change may affect the nation.

TOOLS FOR ASSESSING CLIMATE CHANGE IMPACTS

Scenarios of the Future

Information about the future is valuable, even if it is somewhat uncertain. For example, many people plan their days around weather forecasts with uncertainty conveyed in words or numbers. If there is "a 70% chance of rain" we might take an umbrella with us to work. It may not rain,but if it does, we are prepared. Likewise,although the tools used in this report to explore the possible range of climate change impacts – historical records, computer simulations,and sensitivity analyses – contain uncertainties,their use still provides much valuable information for policymakers,planners,and citizens.

On average over the US, the Hadley model projects a wetter climate than does the Canadian model, while the Canadian model projects a greater increase in temperature than does the Hadley model.

The fact that the climate is changing is apparent from detailed historical records of climate that provide a benchmark for assessing the future. Scientists'understanding of America's future climate – and of the impacts that this altered climate is likely to have on agriculture,human health, water resources,natural ecosystems,and other key issues – has been advanced by the use of computer simulations. Together, the historical record and computer simulations indicate that America's climate is very likely to continue changing in the 21st century, and indeed,that these changes are likely to be substantially larger than those in the 20th century, with significant impacts on our nation.

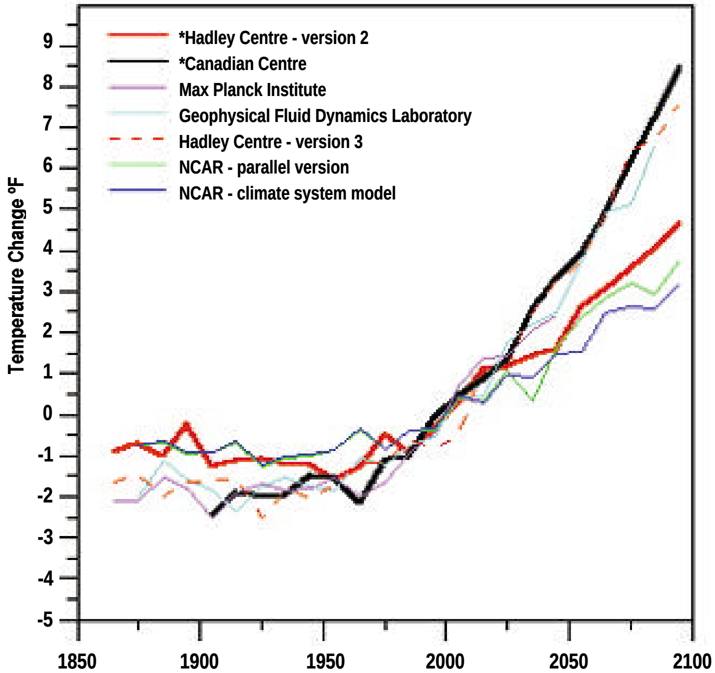
Climate Models used in the US Assessment

Climate models continue to improve,and assumptions about future greenhouse gas emissions continue to evolve. The two primary models used to project changes in climate in this Assessment were developed at the Canadian Climate Centre and the Hadley Centre in the United Kingdom. They have been peer-reviewed by other scientists and both incorporate similar assumptions about future emissions (both approximate the mid-range emissions scenario described on page 4).These models were the best fit to a list of criteria developed for this Assessment.Climate models developed at the National Center for Atmospheric Research (NCAR),NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), NASA's Goddard Institute for Space Studies (GISS),and Max Planck Institute (MPI) in Germany, were also used in various aspects of the Assessment.

While the physical principles driving these models are similar, the models differ in how they represent the effects of some important processes. Therefore,the two primary models paint different views of 21st century climate. On average over the US,the Hadley model projects a much wetter climate than does the Canadian model,while the Canadian model projects a greater increase in temperature than does the Hadley model. Both projections are plausible, given current understanding. In most climate models,increases in temperature for the US are significantly higher than the global average temperature increase. This is due to the fact that all models project the warming to be greatest at middle to high latitudes,partly because melting snow and ice make the surface less reflective of sunlight,allowing it to absorb more heat. Warming will also be greater over land than over the oceans because it takes longer for the oceans to warm.

Uncertainties about future climate stem from a wide variety of factors, from questions about how to represent clouds and precipitation in climate models to uncertainties about how emissions of greenhouse gases will change. These uncertainties result in differences in climate model projections. Examining these differences aids in understanding the range of risk or opportunity associated with a plausible range of future climate changes. These differences in model projections also raise questions about how to interpret model results,especially at the regional level where projections can differ significantly.

Changes in Temperature over the US Simulated by Climate Models



The two primary climate models used in this Assessment have been peer-reviewed and both incorporate similar assumptions about future emissions (both approximate the IPCC "IS92a" scenario with a 1% per year increase in greenhouse gases and growing sulfur emissions).

Simulations from leading climate models of changes in decadal average surface temperature for the conterminous US (excluding Alaska and Hawaii) based on historic and projected changes in atmospheric concentrations of greenhouse gases and sulfate aerosols. The heavy red and black lines indicate the primary models used by the National Assessment. For the 20th century, the models simulate a US temperature rise of about 0.7 to 1.9˚F, whereas estimates from observations range from 0.5 to 1.4˚F; estimates for the global rise are 0.9 to 1.4˚F for models and 0.7 to 1.4˚F for observations, suggesting reasonable agreement. For the 21st century, the models project warming ranging from 3 to 6˚F for the globe and 3 to 9˚F for the US. The two models at the low end of this range assume lower emissions of greenhouse gases than do the other models.

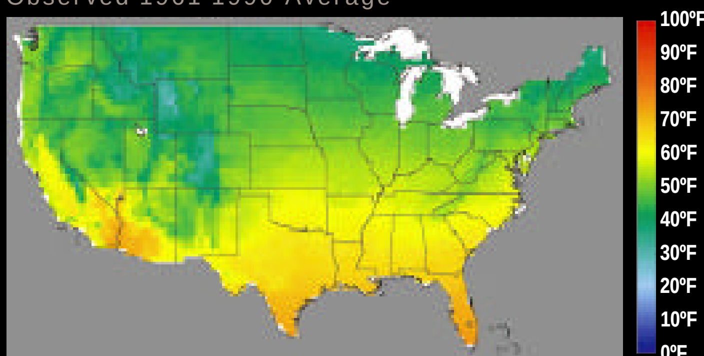
Range of Projected Warming in the 21st Century

	Global	US
*Hadley Model	+5ºF	+5ºF
*Canadian Model	+8ºF	+9ºF
MPI, GFDL and NCAR Models	+3 to 6ºF	+3 to 9ºF

*The two primary models used in the Assessment.

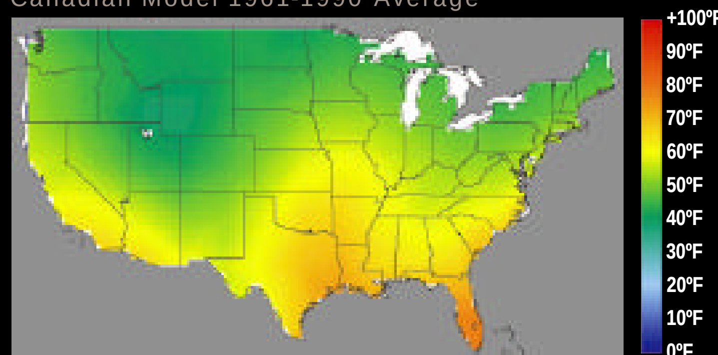
Observed and Modeled Average Annual Temperature

Observed 1961-1990 Average

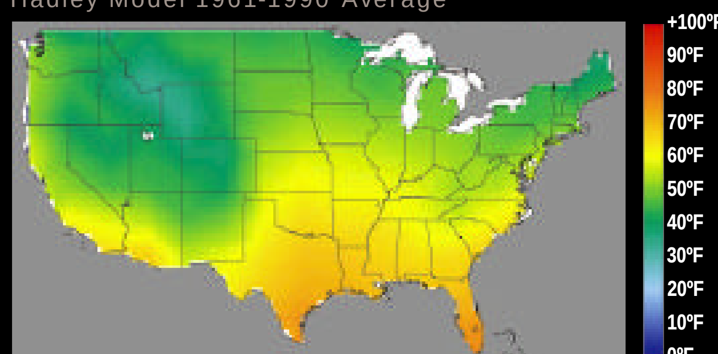


The observed temperature averages for 1961-1990 are similar to the temperatures simulated by the Canadian and Hadley models for the same time period. These are the two primary models used to develop climate change scenarios for this Assessment.

Canadian Model 1961-1990 Average



Hadley Model 1961-1990 Average



TOOLS FOR ASSESSING CLIMATE CHANGE IMPACTS

Interpreting Climate Scenarios

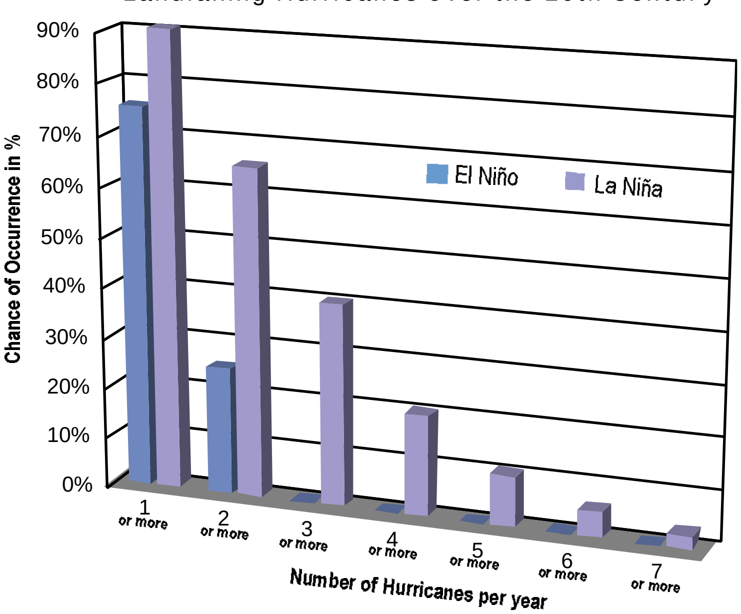
Our level of confidence in climate scenarios depends on what aspect is being considered,and over what spatial scale and time period.Increases in greenhouse gases will cause global temperatures to increase. There is less certainty about the magnitude of the increase,because we lack complete knowledge of the climate system and because we do not know how human society and its energy systems will evolve. Similarly, we are confident that higher surface temperatures will cause an increase in evaporation,and hence in precipitation,but less certain about the distribution and magnitude of these changes.

Model projections of continental-scale and century-long trends are more reliable than projections of shorter-term trends over smaller scales.

The most certain climate projections are those that pertain to large-scale regions,are given as part of a range of possible outcomes,and are applied to trends over the next century. Model projections of continental-scale and century-long trends are more reliable than projections of shorter-term trends over smaller scales. Projections on a decade-by-decade basis,and projections of transient weather phenomena such as hurricanes,are considerably less certain. Two examples serve to illustrate this point. Most climate models project warming in the eastern Pacific, resulting in conditions that look much like current El Niño conditions. When today's existing El Niño pattern is superimposed on this El Niño-like state,El Niño events would likely be more intense,as would their impacts on US weather. Some recent studies suggest that El Niño and La Niña conditions are likely to become more frequent and intense.Other studies suggest little overall change. While these projections must be interpreted with caution,prudent risk management suggests considering the possibility of increases in El Niño and La Niña intensity and frequency.

The projections are less certain regarding changes in the incidence of tropical storms and hurricanes. Some recent studies suggest that hurricanes will become more intense,while others project little change. It is possible that a 5-10% increase in hurricane wind speed will occur by 2100;confirming this remains an important research issue. Perhaps a more important concern is rainfall during hurricanes. One set of model simulations projects that peak precipitation rates during hurricanes will increase 25-30% by the end of the 21st century. Today, El Niño conditions are associated with increased Pacific and decreased Atlantic hurricane frequencies. La Niña is associated with increased Atlantic hurricane frequencies. However, hurricane formation is dependent on a large number of atmospheric and surface conditions. Given these complex dynamics,projections for changes in the frequency and paths of tropical storms must be viewed with caution.

El Niño and La Niña Effects on the Chance of Landfalling Hurricanes over the 20th Century



During El Niño and La Niña years, the chance of landfalling hurricanes on the Gulf and Atlantic coasts changes dramatically, as seen in this chart based on data since 1900. During El Niño years the chance of hurricanes is greatly reduced; no more than two hurricanes have ever made landfall during an El Niño year. On the other hand, during La Niña years, the chance of hurricanes greatly increases; there has been nearly a 40% chance of three or more hurricanes making landfall during a La Niña year.

A Continually Changing Climate and the Potential for Surprises

It is essential to note that the 21st century's climate,unlike that of the preceeding thousand years,is not expected to be stable but is very likely to be in a constant state of change. For example,the duration and amount of ice in the Great Lakes is expected to decrease. It is possible that in the short term an increase in "lake effect" snows would be a consequence during mid-winter, though they would likely decrease in the long term. Across the nation,as climate continues to warm,precipitation is very likely to increasingly fall as rain rather than snow. Such continuously changing climate presents a special challenge for human adaptation.

A continuously changing climate presents a special challenge for human adaptation.

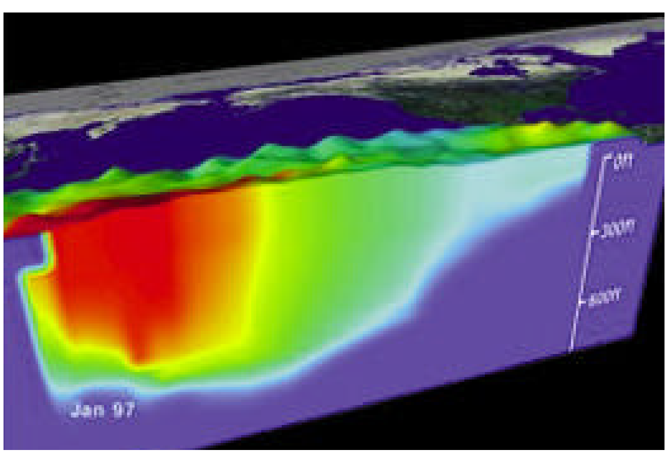
In addition,there is the potential for "surprises." Because climate is highly complex,it is important to remember that it might surprise us with sudden or discontinuous change,or by otherwise evolving quite differently from what is expected. Surprises challenge humans' ability to adapt,because of how quickly and unexpectedly they occur. For example,what if the Pacific Ocean warms in such a way that El Niño events become much more extreme? This could reduce the frequency, but perhaps not the strength,of hurricanes along the East Coast,while on the West Coast,more severe winter storms, extreme precipitation events,and damaging winds could become common. What if large quantities of methane,a potent greenhouse gas currently frozen in icy Arctic tundra and sediments,began to be released to the atmosphere by warming,potentially creating an amplifying "feedback loop" that would cause even more warming? We simply do not know how far the climate system or other systems it affects can be pushed before they respond in unexpected ways.

Because climate is highly complex, it is important to remember that it might surprise us with sudden or discontinuous change.

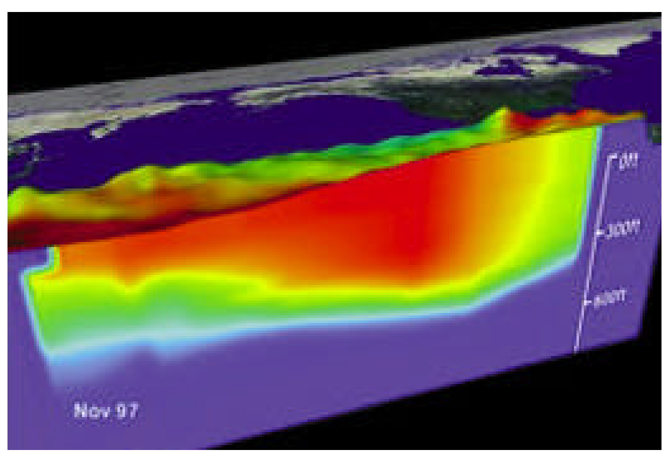
We simply do not know how far the climate system or other systems it affects can be pushed before they respond in unexpected ways.

There are many examples of potential surprises,each of which would have large consequences. Most of these potential outcomes are rarely reported,in this study or elsewhere. Even if the chance of any particular surprise happening is small,the chance that at least one such surprise will occur is much greater. In other words,while we can't know which of these events will occur, it is likely that one or more will eventually occur.

Another caveat is appropriate: climate scenarios are based on emissions scenarios for various gases. The development of new energy technologies,the speed of population growth, and changes in consumption rates each have the potential to alter these emissions in the future,and hence the rate of climate change.



Water temperature profile in the Pacific Ocean, January 1997.



Water temperature profile in the Pacific Ocean, November 1997.

During El Niño conditions, the equatorial pool of warm water (shown in red) expands and moves eastward to span the entire equatorial Pacific east of the dateline. This dramatic warming affects global atmospheric circulation including effects on the jet stream, winter storms, and tropical storms.

LOOKING AT AMERICA'S CLIMATE

Past and Future US Temperature Change

Observations from 1200 weather stations across the US show that temperatures have increased over the past century, on average by almost 1°F (0.6°C). The coastal Northeast, the upper Midwest, the Southwest, and parts of Alaska have experienced increases in the annual average temperature approaching 4°F (2°C) over the past 100 years. The rest of the nation has experienced less warming. The Southeast and southern Great Plains have actually experienced a slight cooling over the 20th century, but since the 1970s have had increasing temperatures as well. The largest observed warming across the nation has occurred in winter.

Average warming in the US is projected to be somewhat greater than for the world as a whole over the 21st century. In the Canadian model scenario, increases in annual average temperature of 10°F (5.5°C) by the year 2100 occur across the central US with changes about half this large along the east and west coasts. Seasonal patterns indicate that projected changes will be particularly large in winter, especially at night. Large increases in temperature are projected over much of the South in summer, dramatically raising the heat index (a measure of discomfort based on temperature and humidity).

In the Hadley model scenario, the eastern US has temperature increases of 3-5°F (2-3°C) by 2100 while the rest of the nation warms more, up to 7°F (4°C), depending on the region.

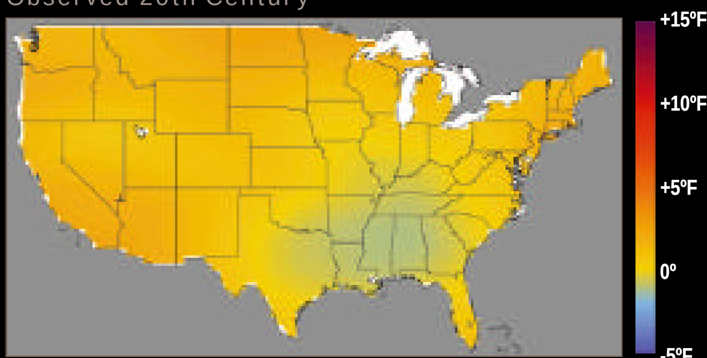
In both models, Alaska is projected to experience more intense warming than the lower 48, and in fact, this warming is already well underway. In contrast, Hawaii and the Caribbean islands are likely to experience less warming than the continental US, because they are at lower latitudes and are surrounded by ocean, which warms more slowly than land.

Both the Canadian and Hadley model scenarios project substantial warming during the 21st century. The warming is considerably greater in the Canadian model, with most of the continental US experiencing increases from 5 to 15°F. In this model, the least warming occurs in the West and along the Atlantic and Gulf Coasts. In the Hadley model, annual temperatures are projected to increase from 3 to 7°F, with the largest warming occurring in the western half of the country.

Temperature Change

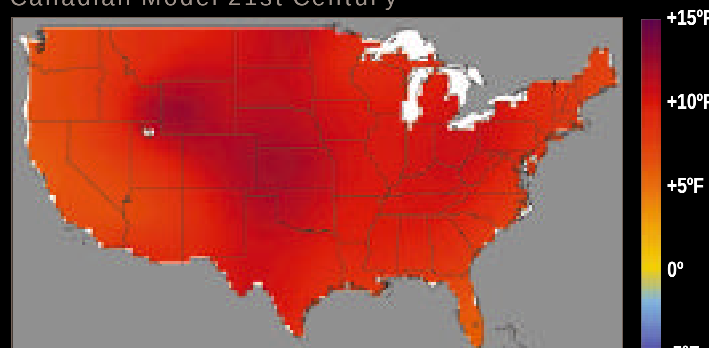
How to read these maps: The color scale indicates changes in temperature in °F over a 100 year period. For example, at 0°F there is no change; at +10°F there is a 10°F increase from the begining to the end of the century.

Observed 20th Century

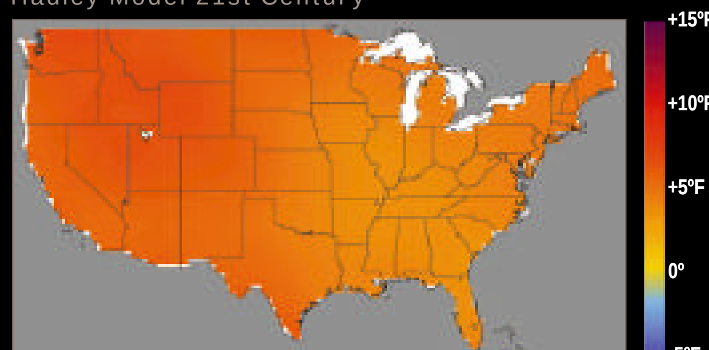


The change in the annual average temperature over the 20th century has a distinctive pattern. Most of the US has warmed, in some areas by as much as 4°F. Only portions of the southeastern US have experienced cooling, and this was primarily due to the cool decades of the 1960s and 1970s. Temperatures since then have reached some of the highest levels of the century.

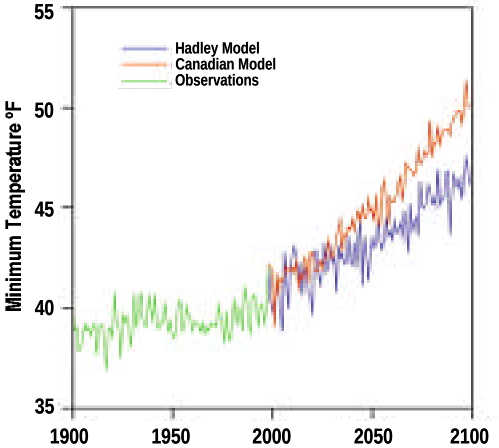
Canadian Model 21st Century



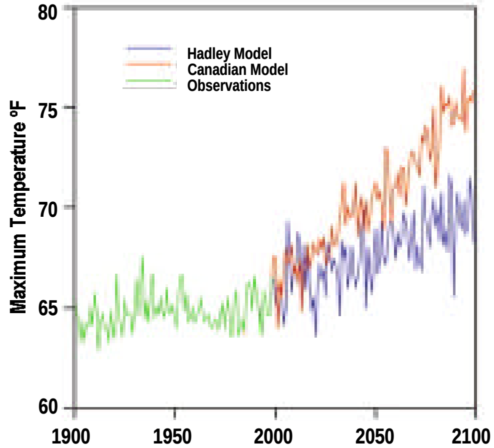
Hadley Model 21st Century



Minimum Temperature in the US (annual average)



Maximum Temperature in the US (annual average)



Average US warming is projected to be somewhat greater than global average warming over the 21st century. Large increases in temperature are projected over much of the South in summer, dramatically raising the heat index (a measure of discomfort based on temperature and humidity).

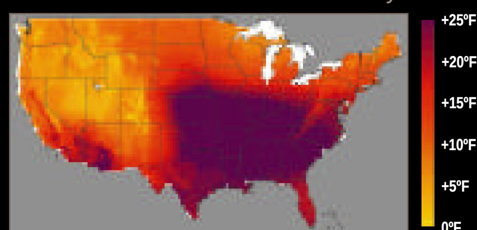
The annual average of minimum and maximum temperatures are compiled from the daily lows and highs. These graphs show the lows and highs, averaged over the year and over the lower 48 states. The green line shows observed temperatues while the red and blue lines are model projections for the future.

The minimum and maximum temperatures are important because, far more than the average, they influence such things as human comfort, heat and cold stress in plants and animals, maintenance of snowpack, and pest populations (many pests are killed by low temperatures; a rise in the minimum often allows more pests to survive).

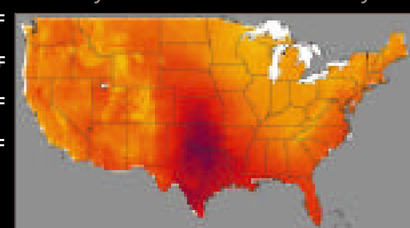
July Heat Index Change

The projected changes in the heat index for the Southeast are the most dramatic in the nation with the Hadley model suggesting increases of 8 to 15ºF for the southernmost states, while the Canadian model projects increases above 25ºF for much of the region.

Canadian Model 21st Century

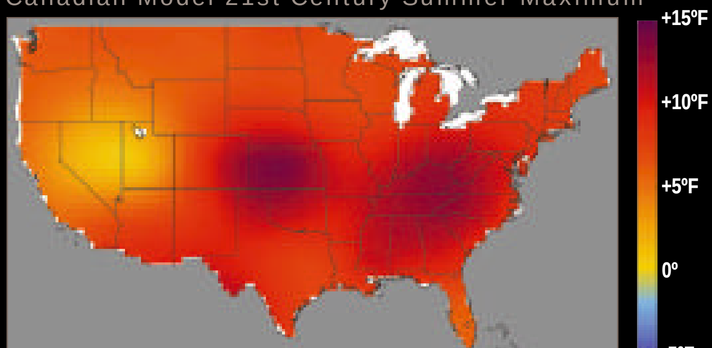


Hadley Model 21st Century

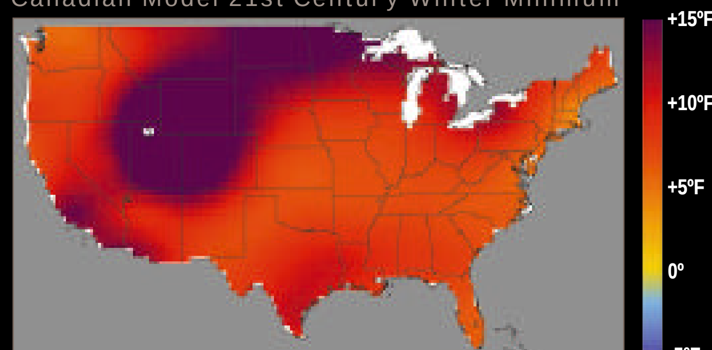


Summer Maximum and Winter Minimum Temperature Change

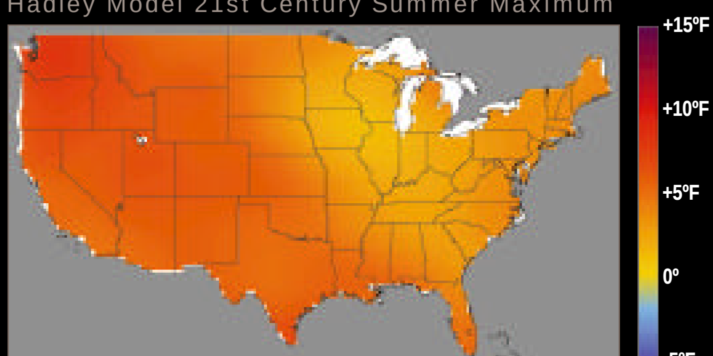
Canadian Model 21st Century Summer Maximum



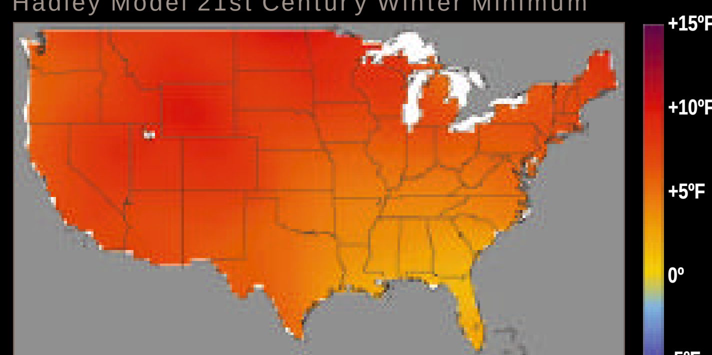
Canadian Model 21st Century Winter Minimum



Hadley Model 21st Century Summer Maximum



Hadley Model 21st Century Winter Minimum



LOOKING AT AMERICA'S CLIMATE

Changes in Precipitation

Average US precipitation has increased by 5-10% over the last century with much of that due to an increase in the frequency and intensity of heavy rainfall. Precipitation increases have been especially noteworthy in the Midwest,southern Great Plains,and parts of the West and Pacific Northwest.Decreases have been observed in the northern Great Plains.

For the 21st century, the Canadian model projects that percentage increases in precipitation will be largest in the Southwest and California,while east of the Rocky Mountains,the southern half of the nation is projected to experience a decrease in precipitation. The percentage decreases are projected to be particularly large in eastern Colorado and western Kansas,and across an arc running from Louisiana to Virginia. Projected decreases in precipitation are most evident in the Great Plains during summer and in the East during both winter and summer. The increases in precipitation projected to occur in the West,and the smaller increases in the Northwest,are projected to occur mainly in winter.

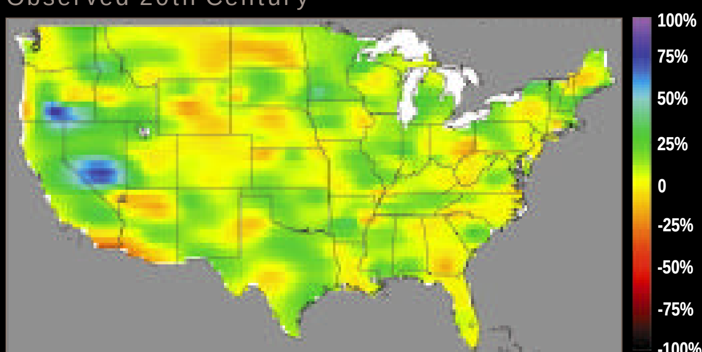
In the Hadley model,the largest percentage increases in precipitation are projected to be in the Southwest and Southern California,but the increases are smaller than those projected by the Canadian model. In the Hadley model,the entire US is projected to have increases in precipitation,with the exception of small areas along the Gulf Coast and in the Pacific Northwest.Precipitation is projected to increase in the eastern half of the nation and in southern California and parts of Nevada and Arizona in summer, and in every region during the winter, except the Gulf States and northern Washington and Idaho.

In both the Hadley and Canadian models,most regions are projected to experience an increase in the frequency of heavy precipitation events. This is especially notable in the Hadley model,but the Canadian model shows the same characteristic.

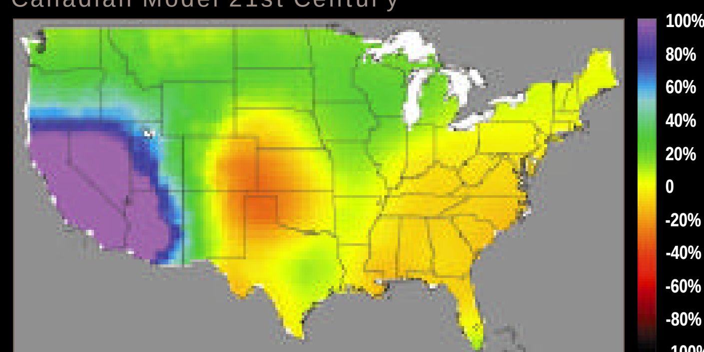
While the actual amounts are modest, the large percentage increases in rainfall projected for the Southwest are related to increases in atmospheric moisture and storm paths. A warmer Pacific would pump moisture into the region and there would also be a southward shift in Pacific Coast storm activity. In the Sierra Nevada and Rocky Mountains, much of the increased precipitation is likely to fall as rain rather than snow, causing a reduction in mountain snow packs.

Precipitation Change

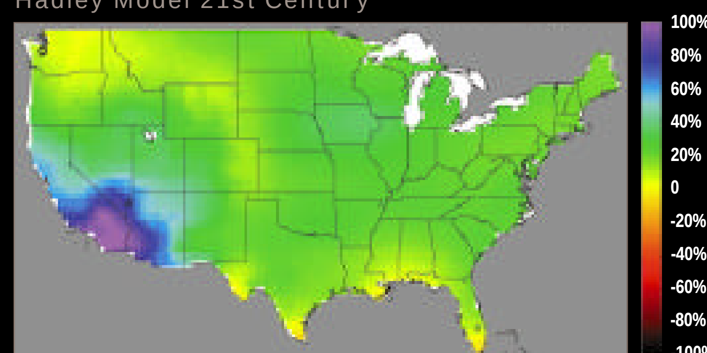
Observed 20th Century



Canadian Model 21st Century



Hadley Model 21st Century



Significant increases in precipitation have occurred across much of the US in the 20th century. Some localized areas have experienced decreased precipitation. The Hadley and Canadian model scenarios for the 21st century project substantial increases in precipitation in California and Nevada, accelerating the observed 20th century trend (some other models do not simulate these increases). For the eastern two-thirds of the nation, the Hadley model projects continued increases in precipitation in most areas. In contrast, the Canadian model projects decreases in precipitation in these areas, except for the Great Lakes and Northern Plains, with decreases exceeding 20% in a region centered on the Oklahoma panhandle. Trends are calculated relative to the 1961-90 average.

This would tend to increase wintertime river flows and decrease summertime flows in the West. Across the Northwest, and the central and eastern US, the two model projections of precipitation change are in less agreement. These differences will be resolved only by improvements in climate modeling.

Changes in Soil Moisture

Soil moisture is critical for both agriculture and natural ecosystems. Soil moisture levels are determined by an intricate interplay among precipitation, evaporation, run-off, and soil drainage. By itself, an increase in precipitation would increase soil moisture. However, higher air temperatures will increase the rate of evaporation and, in some areas, remove moisture from the soil faster than it can be added by precipitation. Under these conditions, some regions are likely to become drier even though their rainfall increases.

In fact, soil moisture has already decreased in portions of the Great Plains and Eastern Seaboard, where precipitation has increased but air temperature has risen.

Since soil moisture projections reflect both changes in precipitation and in evaporation associated with warming, the differences between the two models are accentuated in the soil moisture projections. For example, in the Canadian model, soil moisture decreases of more than 50% are common in the Central Plains due to the combination of precipitation reductions exceeding 20% and temperature increases exceeding 10ºF. In the Hadley model, this same region experiences more modest warming of about 5ºF and precipitation increases of around 20%, generally resulting in soil moisture increases.

Increased drought becomes a national problem in the Canadian model. Intense drought tendencies occur in the region east of the Rocky Mountains and throughout the Mid-Atlantic-Southeastern states corridor. Increased tendencies toward drought are also projected in the Hadley model for regions immediately east of the Rockies. California and Arizona, plus a region from eastern Nebraska to Virginia's coastal plain, experience decreases in drought tendency. The differences in soil moisture and drought tendencies will be significant for water supply, agriculture, forests, and lake levels.

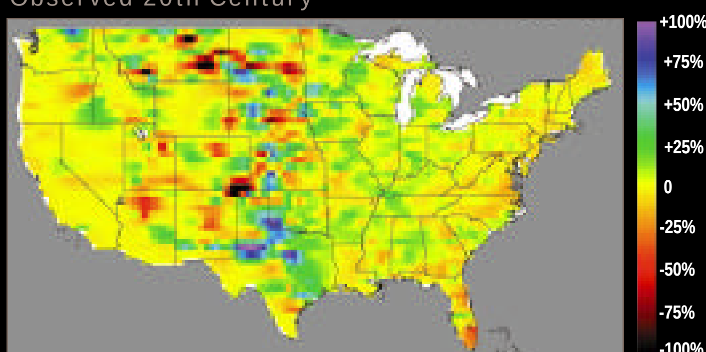
In both the Hadley and Canadian models, most regions are projected to see an increase in the frequency of heavy precipitation events.

Higher air temperatures will increase the rate of evaporation and, in some areas, remove moisture from the soil faster than it can be added by precipitation.

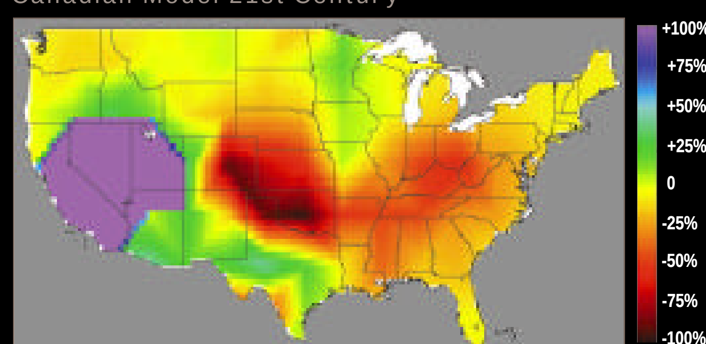
Summer Soil Moisture Change

(Relative to the 1961-90 Average)

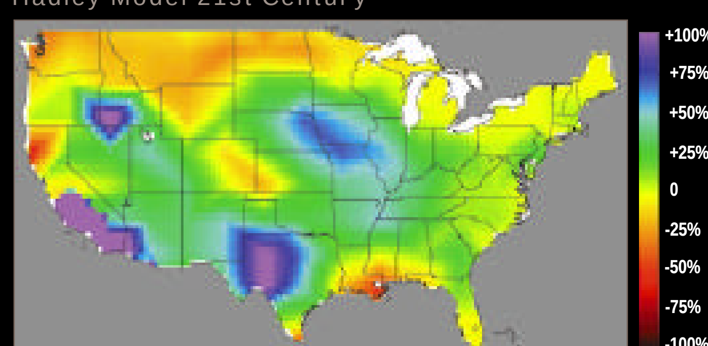
Observed 20th Century



Canadian Model 21st Century



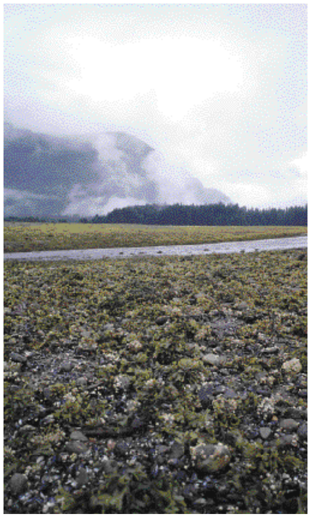
Hadley Model 21st Century



Soil moisture has tended to increase in the central US with decreases in some localized areas. In the Northeast and in the western third of the country, there has been less change in soil moisture, despite the increase in precipitation, due to compensating temperature increases.

The Hadley and Canadian models project strong increases in soil moisture in the Southwest. For the rest of the nation, the Hadley model projects mostly increases while the Canadian model projects mostly decreases, with large decreases in the Central Plains. The contrasts between the two models result from the combination of greater precipitation in the Hadley model and higher air temperatures in the Canadian model.

ECOSYSTEMS IN THE FUTURE



The natural vegetation covering about 70% of the US land surface is strongly influenced both by the climate and by the atmospheric carbon dioxide (CO_2) concentration. To provide a common base of information about potential changes in vegetation across the nation for use in the regional and sector studies,specialized ecosystem models were run using the two major climate model scenarios selected for this Assessment. A summary of the national level results follows. Agricultural and production forestry systems are the focus of separate sections of this Overview report.

What are Ecosystems?

Ecosystems are communities of plants,animals,microbes,and the physical environment in which they exist. They can be characterized by their biological richness, by the magnitude of flows of energy and materials between their constituent species and their physical environment,and by the interactions among the biological species themselves,that is, by which species are predators and prey, which are competitors,and which are symbiotic.

What to Expect with Climate Change

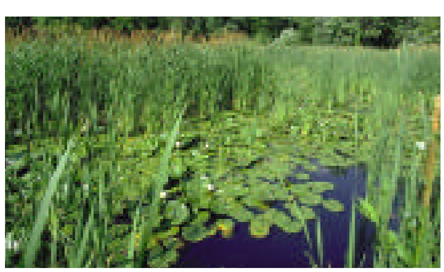
- **Changes in the productivity and carbon storage capacity of ecosystems, decreases in some places and increases in others, are very likely.**
- **Shifts in the distribution of major plant and animal species are likely.**
- **Some ecosystems such as alpine meadows are likely to disappear in some places because the new local climate will not support them or there are barriers to their movement.**
- **In many places, it is very likely that ecosystem services, such as air and water purification, landscape stabilization against erosion, and carbon storage capacity will be reduced. These losses will likely occur in the wake of episodic, large-scale disturbances that trigger species migrations or local extinctions.**
- **In some places, it is very likely that ecosystems services will be enhanced where climate-related stresses are reduced.**

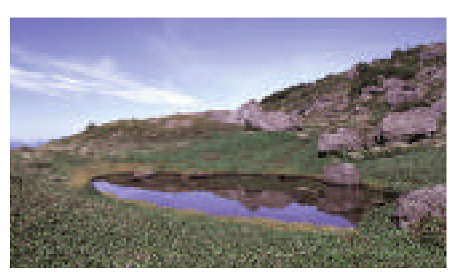
Ecologists often categorize ecosystems by their dominant vegetation – the deciduous broad-leafed forest ecosystems of New England,the short-grass prairie ecosystems of the Great Plains,the desert ecosystems of the Southwest. The term "ecosystem" is used not only to describe natural systems (such as coral reefs,alpine meadows,old growth forests,or riparian habitats),but also for plantation forests and agricultural systems,although these ecosystems obviously differ in many important ways from the natural ecosystems they have replaced.

Ecosystems Supply Vital Goods and Services

While we value natural ecosystems in their own right,ecosystems of all types,from the most natural to the most extensively managed,produce a variety of goods and services that benefit humans. Some of these enter the market and contribute directly to the economy. Thus, forests as sources of timber and pulpwood,and agro-ecosystems as sources of food are important to us. But ecosystems also provide a set of un-priced services that are valuable,but that typically are not traded in the marketplace. There is no current market, for example, for the services that forests and wetlands provide for improving water quality, regulating stream flow, and providing some measure of protection from floods. However, these services are very valuable to society.

Ecosystems are also valued for recreational,aesthetic,and ethical reasons. These are also difficult to value monetarily, but are nevertheless important. The bird life of the coastal marshes of the Southeast and the brilliant autumn colors of the New England forests are treasured components of our regional heritages, and important elements of our quality of life.



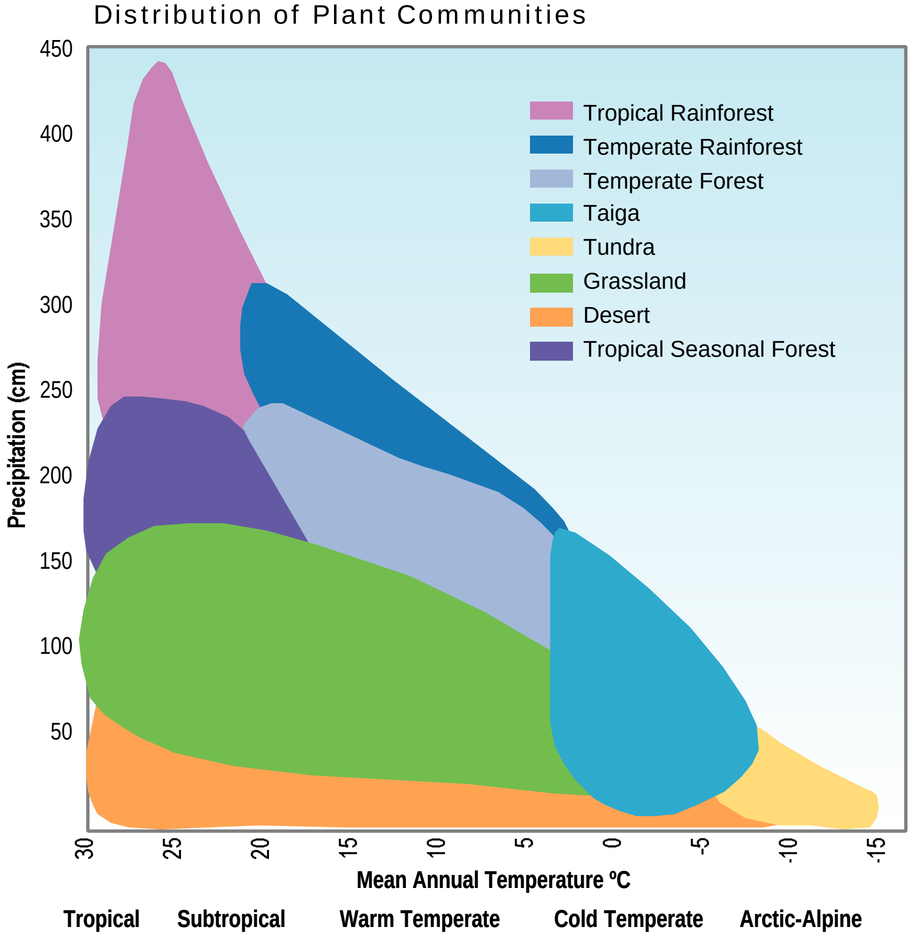


Climate and Ecosystems

Climatic conditions determine where individual species of plants and animals can live, grow, and reproduce. Thus, the collections of species that we are familiar with – the southeastern mixed deciduous forest, the desert ecosystems of the arid Southwest, or the productive grasslands of the Great Plains – are influenced by climate as well as other factors such as land-use. The species in some ecosystems are so strongly influenced by the climate to which they are adapted that they are vulnerable even to modest climate changes. For example, alpine meadows at high elevations in the West exist where they do entirely because the plants that comprise them are adapted to the cold conditions that would be too harsh for other species in the region. The desert vegetation of the Southwest is adapted to the high summer temperatures and aridity of the region. Forests in the east are adapted to relatively high rainfall and soil moisture; if drought conditions were to persist, grasses and shrubs could begin to out-compete tree seedlings, leading to completely different ecosystems.

The species in some ecosystems are so strongly influenced by the climate to which they are adapted that they are vulnerable even to modest climate changes.

There are also many freshwater and marine examples of sensitivities to climate variability and change. In aquatic ecosystems, for example, many fish can breed only in water that falls within a narrow range of temperatures. Thus, species of fish that are adapted to cool waters can quickly become unable to breed successfully if water temperatures rise. Wetland plant species can adjust to rising sea levels by dispersing to new locations, within limits. Too rapid sea-level rise can surpass the ability of the plants to disperse, making it impossible for coastal wetland ecosystems to re-establish themselves.



Both temperature and precipitation limit the distribution of plant communities. The climate (temperature and precipitation) zones of some of the major plant communities (such as temperate forests, grasslands, and deserts) in the US are shown in this figure. Note that grasslands' zone encloses a wide range of environments. This zone can include a mixture of woody plants with the grasses. The shrublands and woodlands of the West are examples of grass/woody vegetation mixes that occur in the zone designated as grasslands.

With climate change, the areas occupied by these zones will shift relative to their current distribution. Plant species are expected to shift with their climate zones. The new plant communities that result from these shifts are likely to be different from current plant communities because individual species will very likely migrate at different rates and have different degrees of success in establishing themselves in new places.

ECOSYSTEMS IN THE FUTURE

Effects of Increased CO_2 Concentration on Plants

The ecosystem models used in this Assessment consider not only changes in climate, but also increases in atmospheric CO_2. The atmospheric concentration of CO_2 affects plant species in ecosystems since it has a direct physiological effect on photosynthesis,the process by which plants use CO_2 to create new biological material. Higher concentrations of CO_2 generally enhance plant growth if the plants also have sufficient water and nutrients,such as nitrogen,to sustain this enhanced growth. For this reason, the CO_2 levels in commercial greenhouses are sometimes boosted in order to stimulate plant growth. In addition,higher CO_2 levels can raise the efficiency with which plants use water. Different types of plants respond at different rates to increases in atmospheric CO_2, resulting in a divergence of growth rates due to CO_2 increase. Some species grow faster, but provide reduced nutritional value. The effects of increased CO_2 level off at some point;thus,continuing to increase CO_2 levels will not result in increased plant growth indefinitely. There is still much we do not understand about the CO_2 "fertilization"effect,its limits,and its direct and indirect implications.

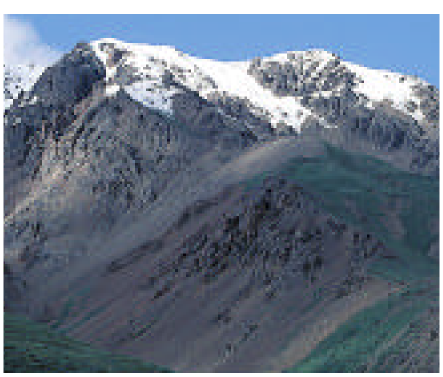
Species Responses to Changes in Climate and CO_2

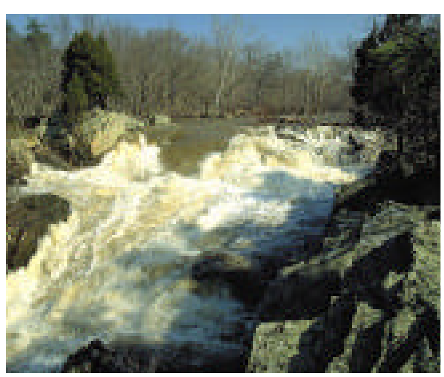
The responses of ecosystems to changes in climate and CO_2 are made up of the individual responses of their constituent species and how they interact with each other. Species in current ecosystems can differ substantially in their tolerances of changes in temperature and precipitation,and in their responses to changes in CO_2; thus,new climate conditions are very likely to result in current ecosystems breaking apart,and new assemblages of species being created. Current ecosystem models have great difficulty in predicting these kinds of biological and ecological responses,thus leading to large uncertainties in projections.

Species in current ecosystems can differ substantially in their tolerances of changes in temperature and precipitation, and in their responses to changes in CO_2; thus, new climate conditions are very likely to result in current ecosystems breaking apart, and new assemblages of species being created.

What the Models Project

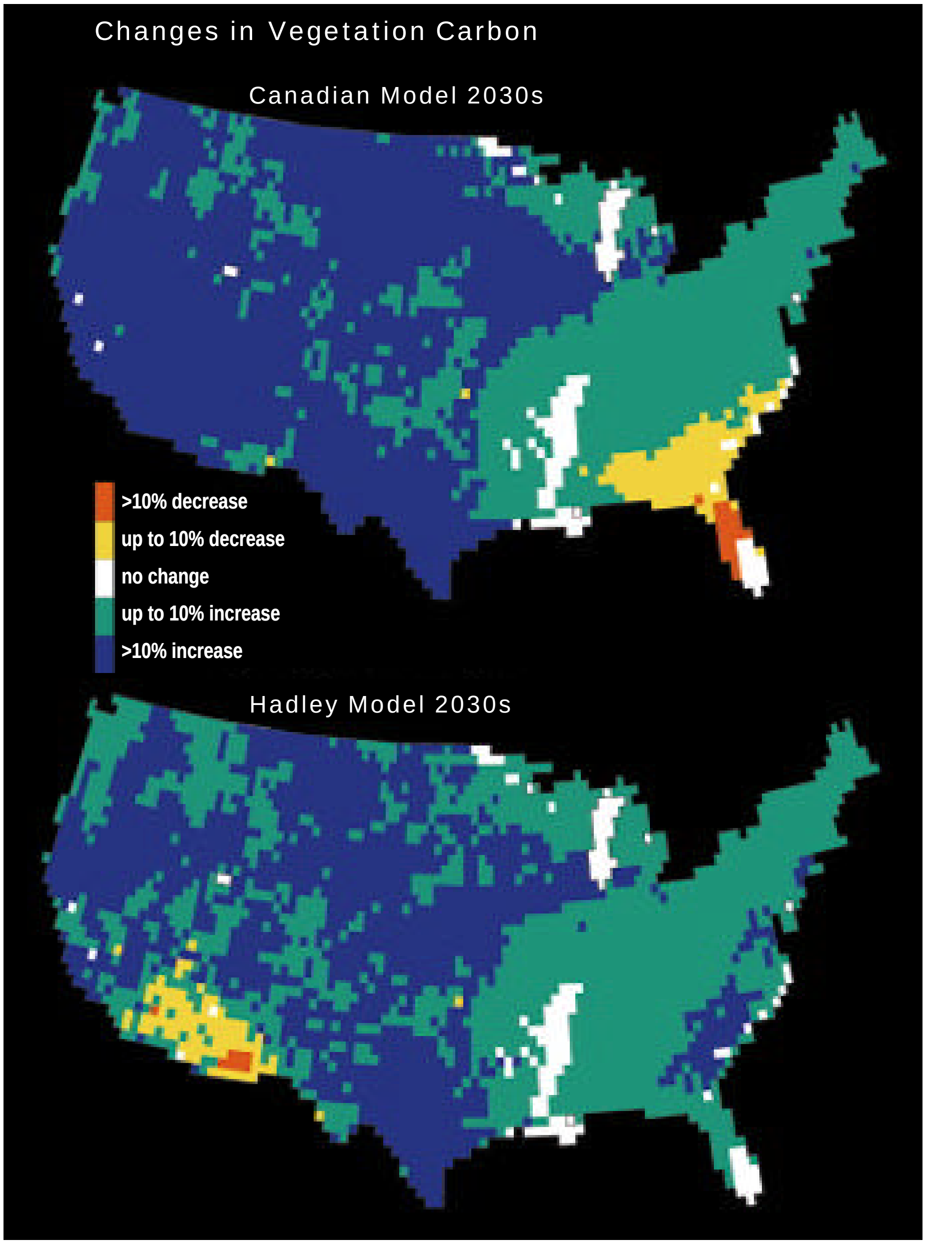
Modeling results to date indicate that natural ecosystems on land are very likely to be highly sensitive to changes in surface temperature,precipitation patterns,other climate parameters,and atmospheric CO_2 concentrations. Two types of models utilized in this Assessment to examine the ecological effects of climate change are biogeochemistry models and biogeography models. Biogeochemistry models simulate changes in basic ecosystem processes such as the cycling of carbon, nutrients,and water (ecosystem function). Biogeography models simulate shifts in the geographic distribution of major plant species and communities (ecosystem structure).



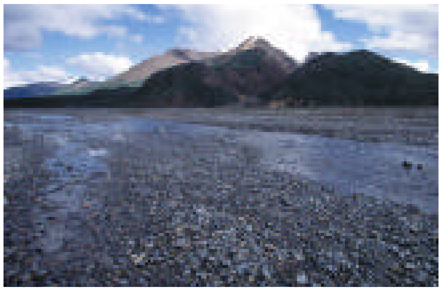


The biogeochemistry models used in this analysis generally simulate increases in the amount of carbon in vegetation and soils over the next 30 years for the continental US as a whole. These probable increases are small – in the range of 10% or less,and are not uniform across the country. In fact, for some regions the models simulate carbon losses over the next 30 years. One of the biogeochemistry models,when operating with the Canadian climate scenario,simulates that by about 2030,parts of the Southeast will likely lose up to 20% of the carbon from their forests. A carbon loss by a forest is treated as an indication that it is in decline. The same biogeochemistry model,when operating with the Hadley climate scenario,simulates that forests in the same part of the Southeast will likely gain between 5 and 10% in carbon in trees over the next 30 years.

Why do the two climate scenarios result in opposite ecosystem responses in the Southeast? The Canadian climate scenario shows the Southeast as a hotter and drier place in the early decades of the 21st century than does the Hadley scenario. With the Canadian scenario, forests will be under stress due to insufficient moisture,which causes them to lose more carbon in respiration than they gain in photosynthesis. In contrast,the Hadley scenario simulates relatively plentiful soil moisture, robust tree growth,and forests that accumulate carbon.



The maps above show projections of relative changes in vegetation carbon between 1990 and the 2030s for two climate scenarios. Under the Canadian model scenario, vegetation carbon losses of up to 20% are projected in some forested areas of the Southeast in response to warming and drying of the region by the 2030s. A carbon loss by forests is treated as an indication that they are in decline. Under the same scenario, vegetation carbon increases of up to 20% are projected in the forested areas in the West that receive substantial increases in precipitation. Output from TEM (Terrestrial Ecosystem Model) as part of the VEMAP II (Vegetation Ecosystem Modeling and Analysis Project) study.



ECOSYSTEMS IN THE FUTURE

Will disturbances caused by climate change be regular and small or will they be episodic and large? The latter category of disturbances is likely to have a negative impact on ecosystem services; the ability of ecosystems to cleanse the air and water, stabilize landscapes against erosion, and store carbon, for example, are very likely to be diminished.

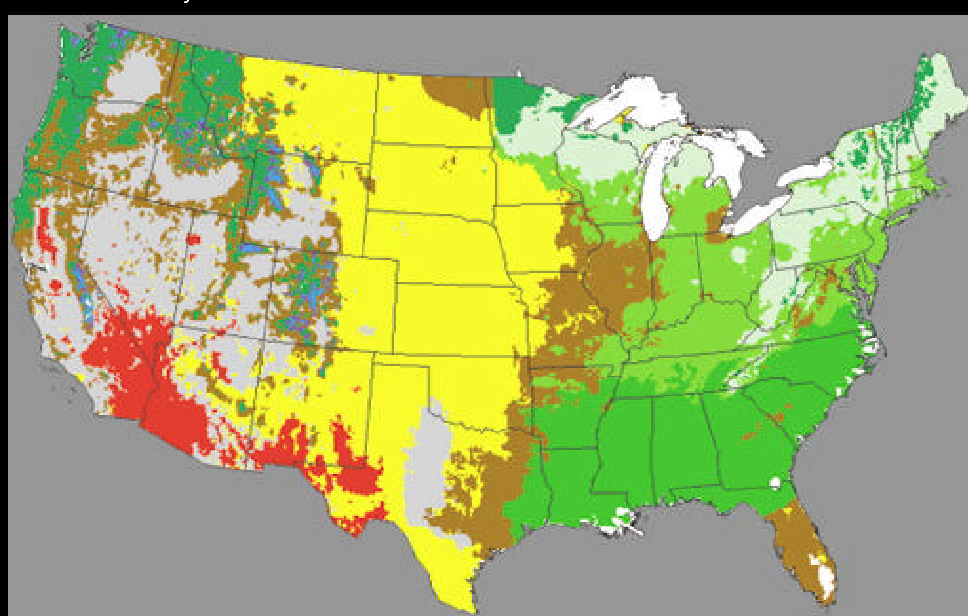
Prolonged stress due to insufficient soil moisture can make trees more susceptible to insect attack,lead to plant death,and increase the probability of fire as dead plant material adds to an ecosystem's "fuel load." The biogeography models used in this analysis simulate at least part of this sequence of climate-triggered events in ecosystems as a prelude to shifts in the geographic distribution of major plant species. One of the biogeography models,when operating with the Canadian climate scenario,simulates that towards the end of the 21st century, a hot dry climate in the Southeast will result in the replacement of the current mixed evergreen and deciduous forests by savanna/woodlands and grasslands,with much of the change involving fire. This change in habitat type in the Southeast would imply that the animal populations of the region would also change, although the biogeography models are not designed to simulate these changes. The same biogeography model,when operating with the Hadley scenario,simulates a slight northward expansion of the mixed evergreen and deciduous forests of the Southeast with no significant contraction along the southern boundary. Other biogeography models show similar results.

Major Uncertainties

Major uncertainties exist in the biogeochemistry and biogeography models. For example,ecologists are uncertain about how increases in atmospheric CO_2 affect the carbon and water cycles in ecosystems. What they assume about these CO_2 effects can significantly influence model simulation results. One of these models was used to show the importance of testing these assumptions.Consideration of climate change alone

Ecosystem Models

Current Ecosystems



Maps of current and projected potential vegetation distribution for the conterminous US. Potential vegetation means the vegetation that would be there in the absence of human activity. Changes in vegetation distribution by the end of the 21st century are in response to two climate scenarios, the Canadian and the Hadley. Output is from MAPSS (Mapped Atmosphere-Plant-Soil System).

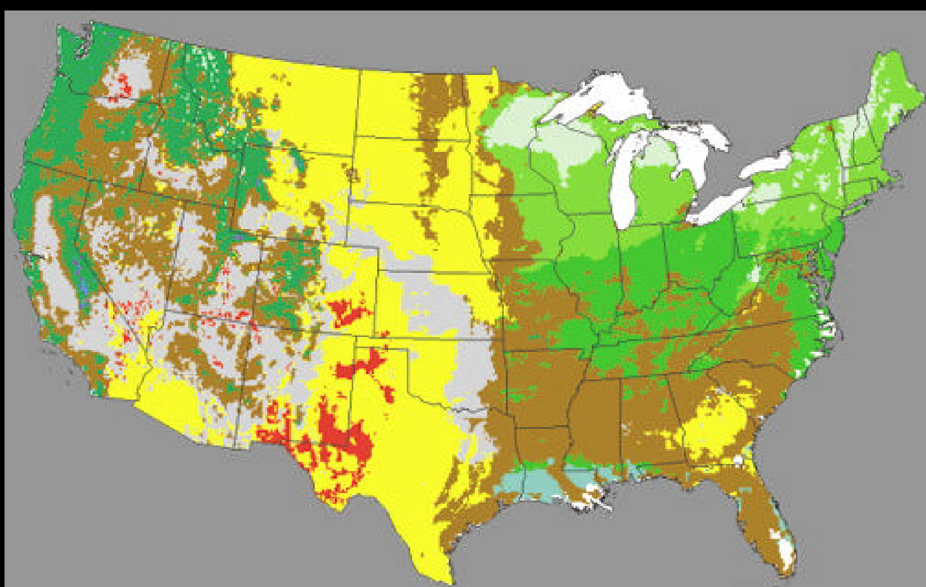
- Tundra
- Taiga / Tundra
- Conifer Forest
- Northeast Mixed Forest
- Temperate Deciduous Forest
- Southeast Mixed Forest
- Tropical Broadleaf Forest
- Savanna / Woodland
- Shrub / Woodland
- Grassland
- Arid Lands

results in a 10% decrease in plant productivity. Consideration of both climate and CO_2 effects results in an increase in plant productivity of 10%.This illustrates the importance of resolving uncertainties about the effects of CO_2 on ecosystems.

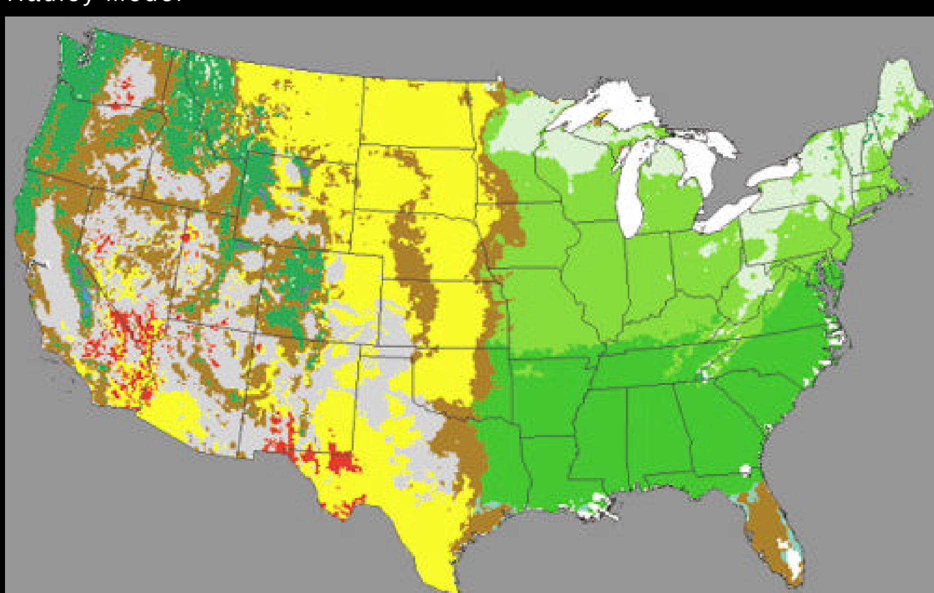
Ecologists are uncertain about how increases in atmospheric CO_2 affect the carbon and water cycles in ecosystems. What they assume about these CO_2 effects can significantly influence model simulation results.

With respect to biogeography models,scientists are uncertain about the frequency and size of disturbances produced by factors such as fire and pests that initiate changes in the distribution of major plant and animal species. Will disturbances caused by climate change be regular and small or will they be episodic and large? The latter category of disturbances is likely to have a negative impact on ecosystems services; the ability of ecosystems to cleanse the air and water, stabilize landscapes against erosion,and store carbon, for example, are very likely to be diminished.

Canadian Model



Hadley Model



A substantial portion of the Southeast's mixed forest is replaced by a combination of savanna and grassland in response to fire caused by warming and drying of the region as projected by the Canadian model. The Hadley climate projection leads to a simulated northward expansion of the mixed forest.

These particular model runs show the response of vegetation to atmospheric concentrations of CO_2 that have stabilized at about 700 parts per million, approximately twice the present level.

In the Southwest, large areas of arid lands are replaced with grassland or shrub/woodland in response to increases in precipitation projected by both models.

Tundra
Taiga / Tundra
Conifer Forest
Northeast Mixed Forest
Temperate Deciduous Forest
Southeast Mixed Forest
Tropical Broadleaf Forest
Savanna / Woodland
Shrub / Woodland
Grassland
Arid Lands