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REPORTS TO THE NATION

On Our Changing Planet

Our Changing Climate

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Cover: Peruvian coast and Andes Mountains looking south. NASA Space Shuttle.

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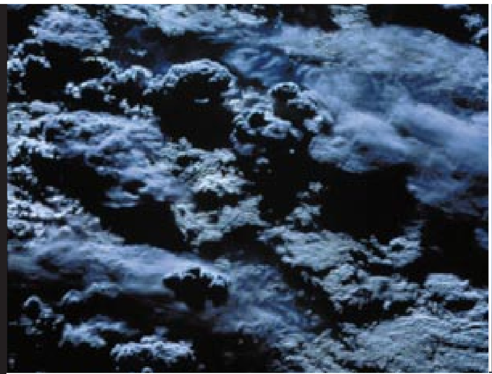
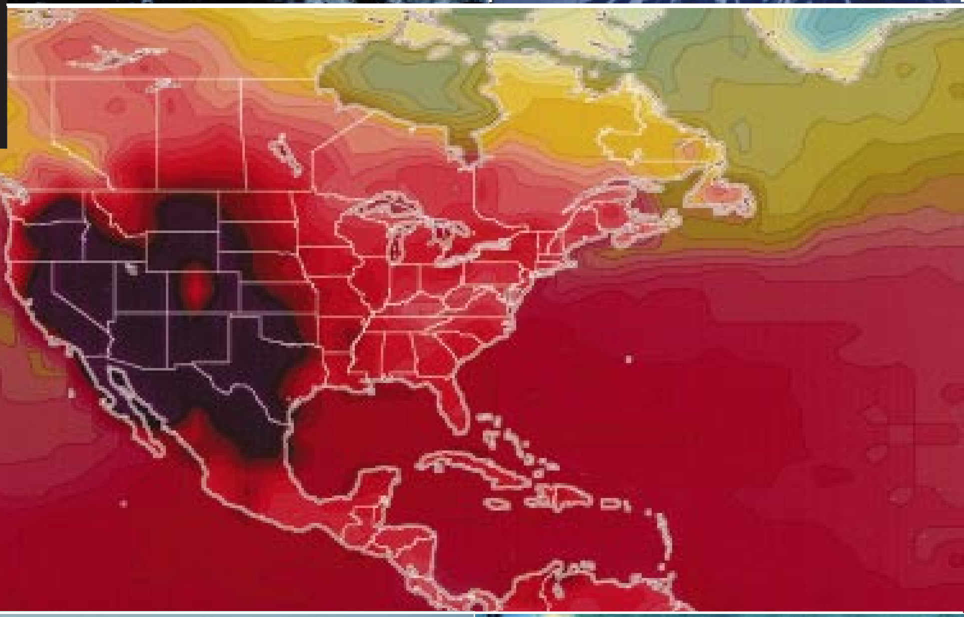
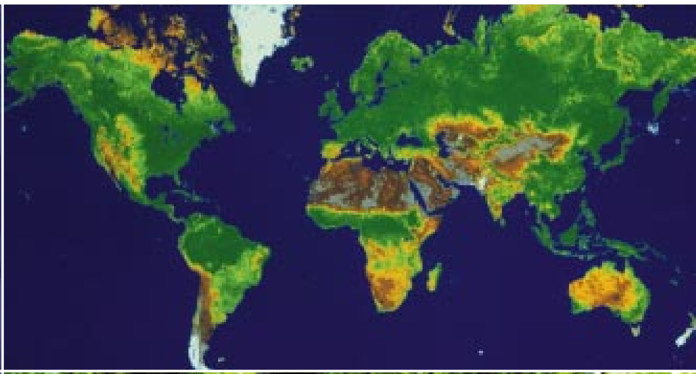
We have now entered an era when actions by humanity may have as much influence on Earth's climate as the natural processes that have driven climate change in the past. Our future climate will be partly of our own making.

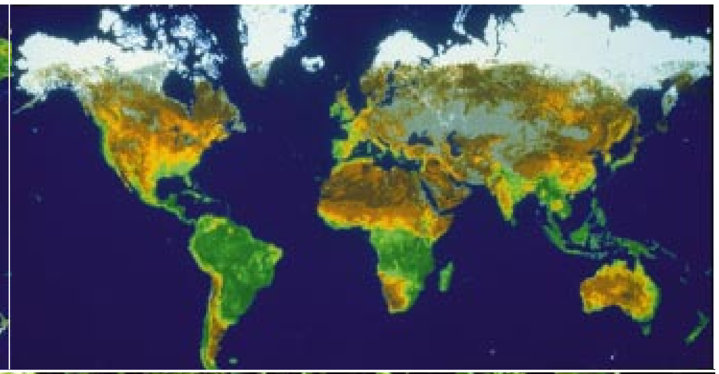
Favorable temperatures and abundant water near the surface of Earth support a rich diversity of life. Patterns of temperature and rainfall have shifted significantly over time in response to natural forces, and these changes in climate have had important effects on people and the natural world in which we live.

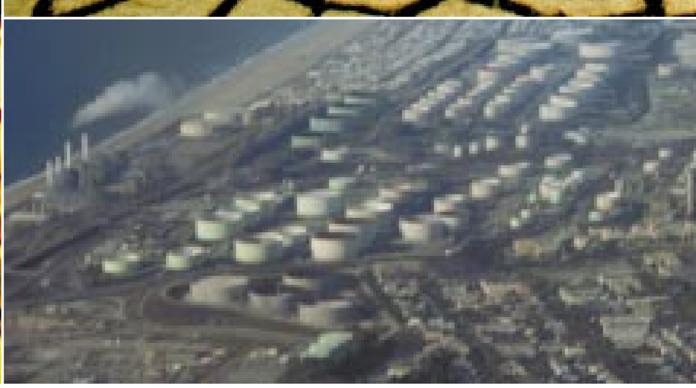


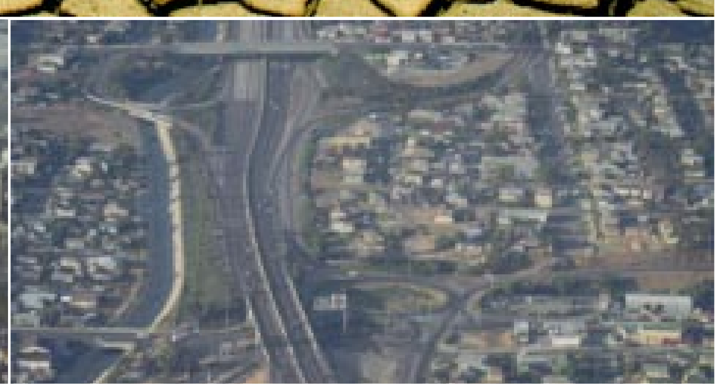


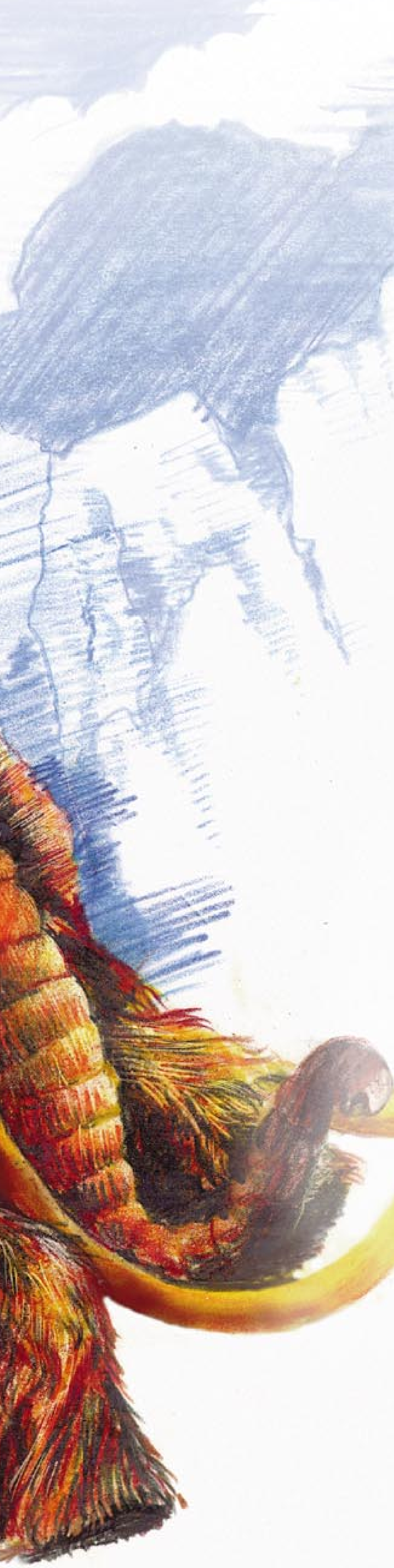
Life on Earth responds to the climate and also helps to shape it.







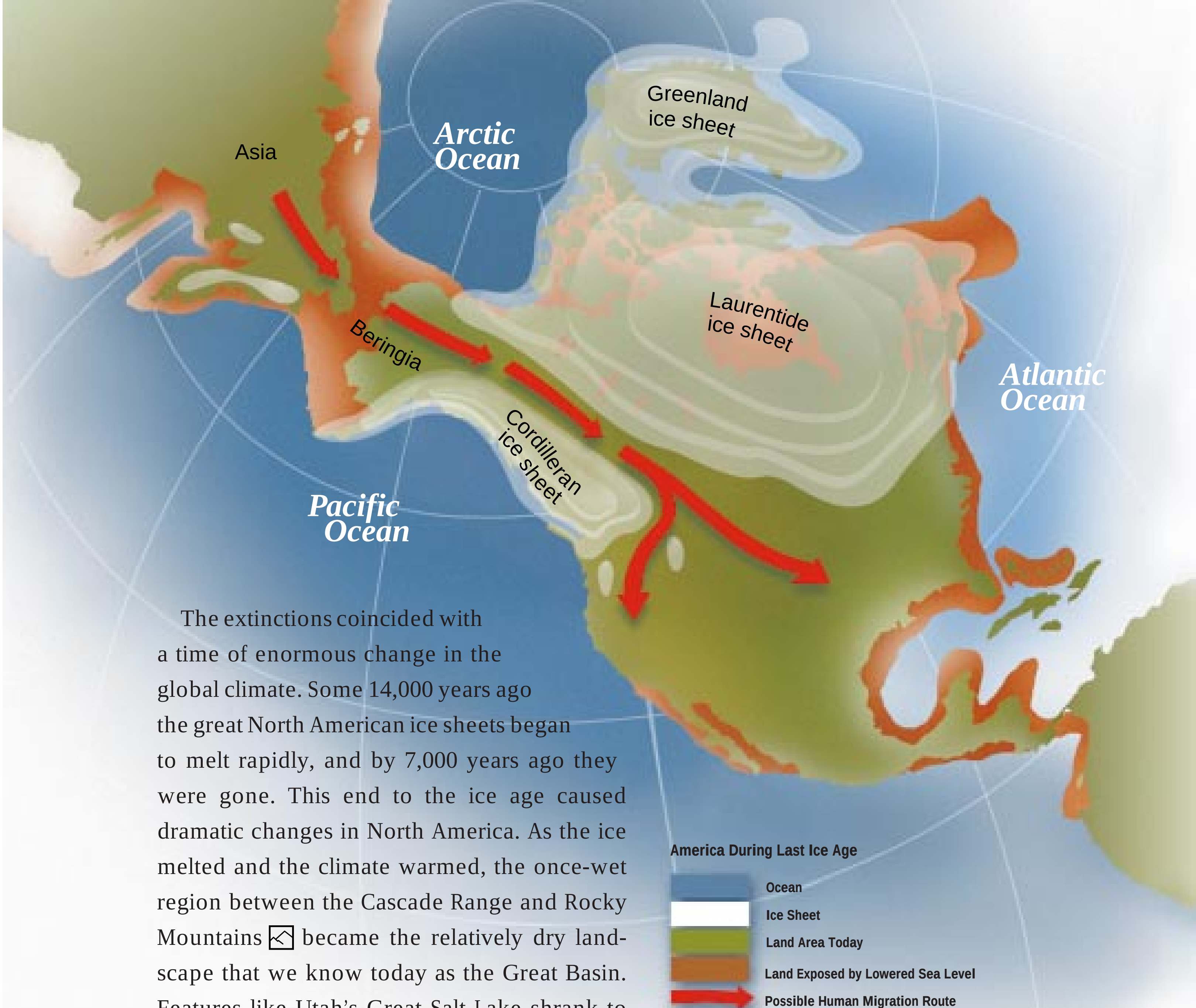




Our Changing Climate

CLIMATE AND AMERICAN PEOPLE Climate has always had a profound effect on life in America. The first people arrived in America between 15,000 and 30,000 years ago. During that time much of North America was covered by two great ice sheets that were nearly two miles thick in places. One ice sheet followed the coastal mountains from Alaska to Washington State, and another extended from the eastern slope of the Rocky Mountains to the Atlantic Ocean and from the Arctic Ocean to Ohio. Because so much water was piled up on land in ice sheets, the sea level was about 350 feet lower at the peak of the last ice age about 20,000 years ago than it is today. The lowered sea exposed a wide plain between Siberia and Alaska, creating a land bridge across the Bering Sea. Genetic, linguistic, and fossil evidence suggests that the first humans in America came from northeast Asia, and it is likely that the ice age climate made it possible for these people to walk across the land bridge between Siberia and Alaska. After crossing this plain, these hardy people could have made their way south past the great ice sheets and spread across America.

We know that some of these early Americans were big game hunters. Their camps are marked by distinctive fluted spear points which they used to hunt mastodons—extinct relatives of the modern elephant. They also shared the land with saber-toothed cats, woolly rhinoceroses, and giant ground sloths. These and a variety of other species all became extinct about 10,000 years ago. Some researchers argue that efficient human hunters caused these extinctions, but others believe that environmental change was the key factor.



Ice sheets and lowered sea level at the time of the last glacial maximum opened an access route from Asia to America. The current continental outline is given for reference.

The extinctions coincided with a time of enormous change in the global climate. Some 14,000 years ago the great North American ice sheets began to melt rapidly, and by 7,000 years ago they were gone. This end to the ice age caused dramatic changes in North America. As the ice melted and the climate warmed, the once-wet region between the Cascade Range and Rocky Mountains became the relatively dry landscape that we know today as the Great Basin. Features like Utah's Great Salt Lake shrank to shadows of their former selves. Fifteen thousand years ago this body of water was 1200 feet deeper and covered an area the size of Lake Michigan.

Such changes had a marked impact on ice age plants and animals. Cold-loving spruce trees, for example, withdrew their range northward by about a thousand miles, giving way to grassland and broadleaf trees. Mastodons and other large mammals that preferred cold climates may not have been able to adapt to the warmer, drier conditions. As their favorite game animal disappeared, the earliest Americans would also have been forced to adapt.

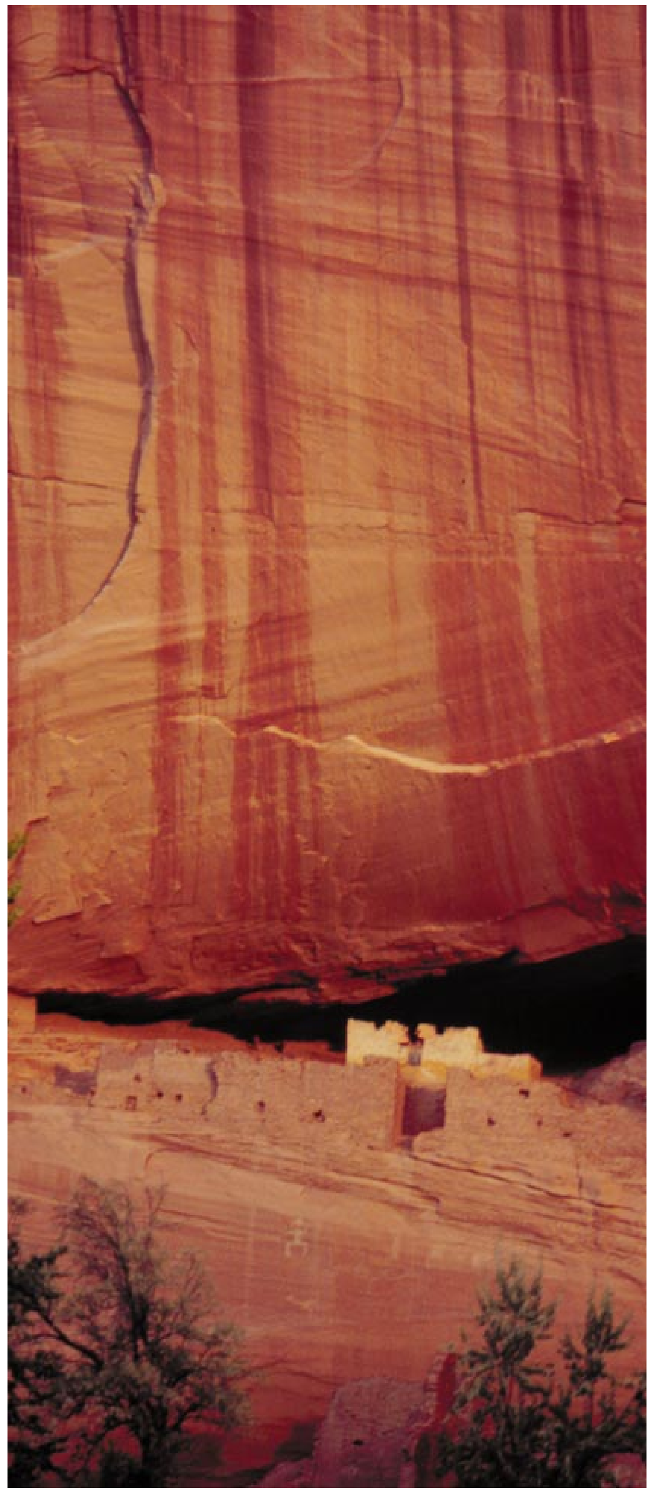
The effect of climate on human settlement of America continued into medieval times. The first Europeans to set foot on America were Vikings who settled Greenland under the leadership of Eric the Red in about 1000AD. His son, Leif Erikson, led an expedition to colonize America that probably settled in Newfoundland. The colony in Greenland was abandoned in about 1400AD when cooler temperatures associated with the Little Ice Age made farming

there too difficult. Farther to the south, climate changes also affected the civilizations set up by the earlier Asian immigrants to America. The Anasazi people of the Four Corners region of the southwestern United States provide an interesting example. They had an economy centered around corn farming, and built large dwellings in river valleys and along the ridges between canyons. The most famous of these are the cliff dwellings and pueblos of the Mesa Verde region near the junction of Colorado, Utah, Arizona, and New Mexico. Beginning about 1150AD the Four Corners region experienced a series of profound droughts, and by 1300AD the Anasazi had abandoned this area.

Although we have more advanced technology than the Anasazi, modern residents of the United States are also affected by variations in our climate. Between 1934 and 1937 parts of Texas, Oklahoma, Colorado, New Mexico, and Kansas became known as the Dust Bowl when severe drought afflicted the area. Clouds of dust rolled across the vast area affected by the drought, and many people were forced to move away to find new sources of livelihood.

Earth's Climate: A Dynamic System

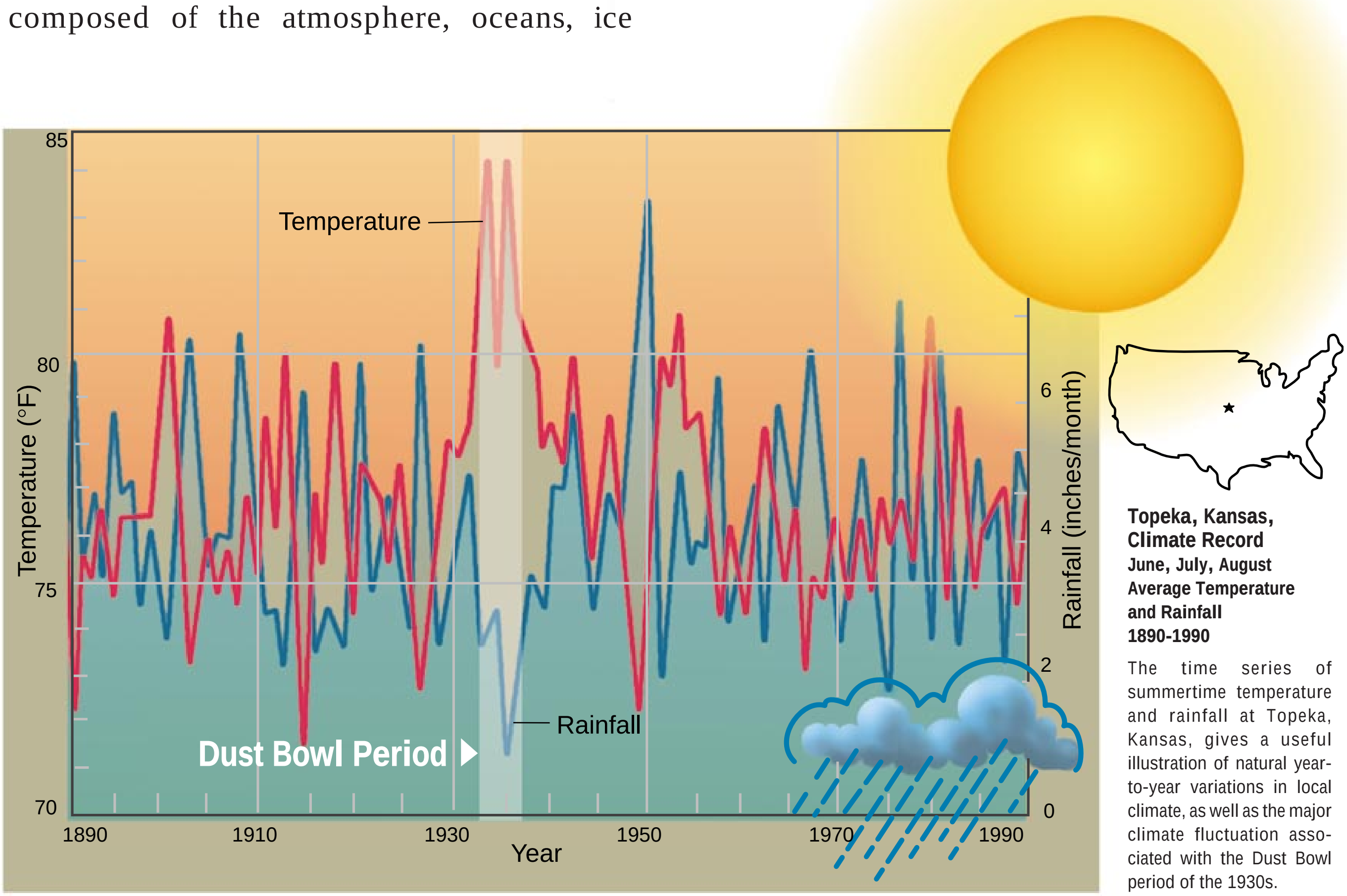
Weather changes both rapidly and slowly. The passage of a thunderstorm can change a bright sunny day into a dark, windy, rainy one in less than an hour. Farmers know that in one year the amount and timing of rainfall can be nearly ideal



Canyon de Chelly Anasazi ruin, Arizona.

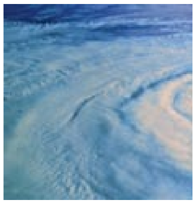
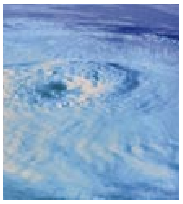
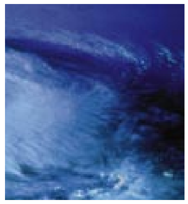
for growing crops, while the next year might bring drought or floods. In some years no hurricanes reach the Atlantic Coast, while in other years coastal states are battered by one storm after another.

In many cases, variations in weather are random; like the lucky and unlucky spells of a gambler they occur without any apparent cause. The atmosphere, in isolation, has only short-term memory, and so acting alone it cannot produce random variations that persist month after month. But the climate is determined by the workings of the climate system, which is composed of the atmosphere, oceans, ice sheets, land, and the plants, animals, and people that inhabit them. Because the ocean has a large capacity to store and release heat, it gives the climate system a long memory that can result in variations lasting from seasons to centuries. The number of hurricanes in the Atlantic, for example, is known to vary from year to year in synchrony with subtle shifts in the sea surface temperature and seasonal wind patterns. Similarly, long-term effects can result from changes in the biology and chemistry of the climate system. For example, life in the sea controls the flux of carbon from atmospheric



Topeka, Kansas, Climate Record
June, July, August Average Temperature and Rainfall 1890-1990

The time series of summertime temperature and rainfall at Topeka, Kansas, gives a useful illustration of natural year-to-year variations in local climate, as well as the major climate fluctuation associated with the Dust Bowl period of the 1930s.

carbon dioxide into ocean sediments.

If weather varies over long intervals and climate does too, how do we distinguish one from the other? One simple way to think of it is that climate is what we expect; weather is what we get. To describe climate, researchers look at the average weather over a number of years in a particular region during a particular season. Random variations in the weather from year to year usually balance each other in these averages and do not affect the mean climate.

But sometimes abnormal temperature or rainfall persists for a few years or even a decade. We can think of these slow shifts in weather as climate fluctuations. One important source of climate fluctuations is the El Niño-Southern Oscillation of the tropical Pacific. The ocean and atmosphere are closely linked in this region and together produce important climate fluctuations from one year to the next that have a significant impact on the seasonal rainfall there and in regions far removed from the tropical Pacific. Events ranging from droughts in Australia to flooding in some parts of the U.S. result from the intimate slow dance of the atmosphere with the ocean.

Another example of a climate fluctuation is the Dust Bowl of the 1930s in the United States. While it had a very serious influence on the lives of many people, it lasted only a few years and did not represent a long-term change in the climate. We can't give a simple explanation for the warm, dry years that produced the Dust Bowl event of the 1930s, but it is probably an example of a natural fluctuation of the climate system. The effects of this fluctuation were worsened by the agricultural practices in use in the region at that time, and improved soil conservation techniques were adopted after the Dust Bowl experience.

Climate varies not only from year to year and decade to decade but also on time scales of centuries or longer. Great continental ice sheets have appeared and disappeared again and again over the last several million years. What caused these long-term variations? Scientists believe they stem from something other than the internal workings of the climate system. Just as a baseball player's home run statistics might change when the fences are moved closer to home plate, the weather statistics can change as a result of shifts in the planet's external conditions.

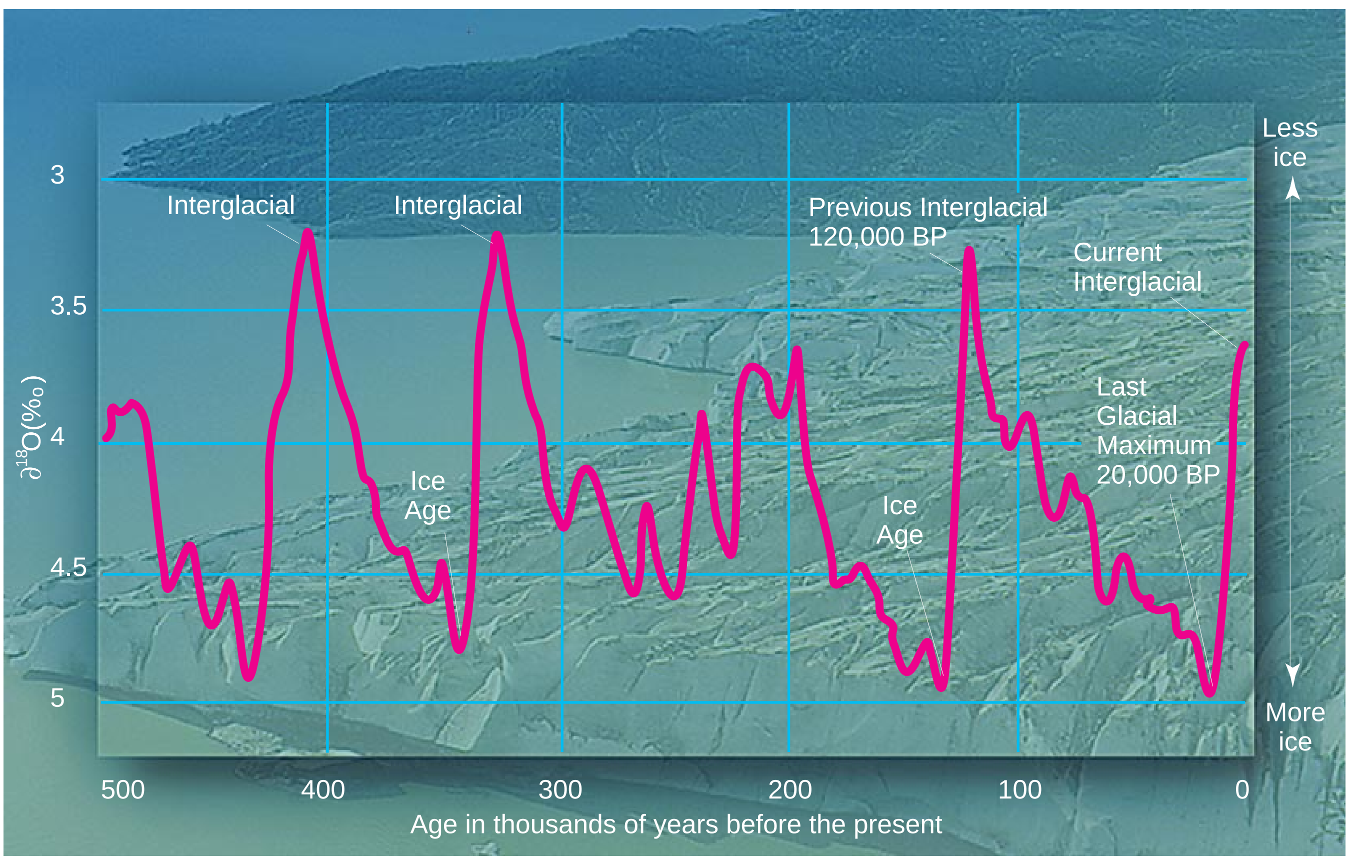
Why Does Earth's Climate Change?

In 1924 the Serbian mathematician Milutin Milankovitch offered a theory for what causes the advances and retreats of ice sheets. He hypothesized that the critical factor in determining ice sheet growth is the amount of sunshine reaching high latitudes of the Northern Hemisphere in the summer. We call the energy provided by sunshine the insolation. Milankovitch predicted that ice sheets would grow when the insolation reaching the high

latitude continents was less than normal during summer, since this would allow snow cover to last through the melting season and gradually accumulate over the centuries.

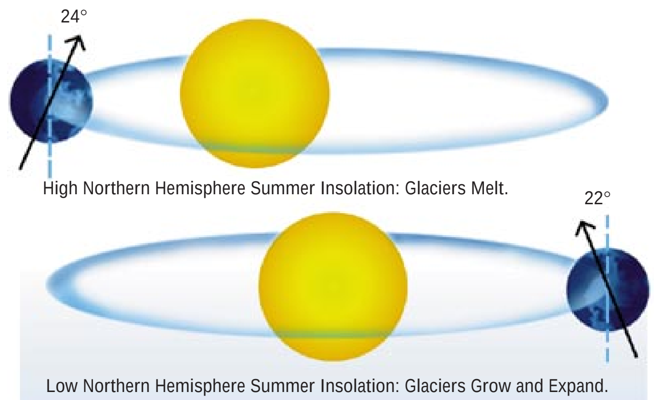
He showed that changes of insolation result from subtle variations in Earth's orbit. Today the Earth's axis of rotation is tilted about 23.5 degrees relative to the plane of the Earth's orbit about the sun, and this tilt gives us pronounced seasons in middle and high latitudes. This tilt angle varies between 22 and 24.5 degrees with a period of about 41,000 years. The amount by which Earth's orbit deviates from a perfect circle also varies, with periods around 100,000 and 400,000 years. And the day of the year when Earth is closest to the sun—currently January 3rd—varies on a 23,000-year cycle. The effects of all these orbital variations on insolation are largest in middle and high latitudes, where colder temperatures make the development of large ice sheets possible.

Over the last several decades Milankovitch's theory has received a large boost. Modern techniques enable scientists to estimate past



Oxygen Isotope—Global Ice Volume Past 500,000 Years

The oxygen isotope record in ocean sediments can be used to estimate the mass of water contained in continental ice sheets in the past. Many times over the past 3 million years the global ice volume has varied dramatically from ice age conditions to interglacial conditions more like today's. This plot shows the variation of global ice volume over the last 500,000 years, plotted upside down so that peaks indicate warm intervals and low points indicate ice ages.



Milankovitch's Orbital Parameter Theory
Milankovitch theorized that subtle variations in Earth's orbit can add up to extreme shifts in climate. A large tilt in Earth's axis of rotation combined with an eccentric orbit and a summertime date for Earth's closest approach to the sun (top) causes more sunshine to reach high latitudes of the Northern Hemisphere during summer. The result is a warm climate. The opposite extreme, in which the tilt of Earth's axis is smaller, its orbit is less eccentric, and it is closer to the sun during the Northern Hemisphere's winter (bottom), causes snow cover to last through the melting season. The accumulation of snow over many seasons produces ice age conditions.

amounts of land ice, based on information contained in layered ocean sediments. For the last several million years, the ice sheets have varied with the same rhythm as Earth's orbit. In agreement with the Milankovitch theory, global ice volume peaked at about the same times that summertime insolation at high latitudes dipped. The period of rapid ice sheet melting about 10,000 years ago occurred at a time when greater summertime insolation was reaching the high-latitude continents of the Northern Hemisphere.

While external shifts of insolation appear to be a pacemaker of ice ages, the nature and magnitude of the resulting climate changes are still determined by processes that take place within Earth's climate system. In order for the climate to swing from ice age to warmer conditions, the climate system must amplify the response to Earth's orbital changes. One way climate change can be amplified is via a process known as ice-albedo feedback. "Albedo" is a measure of how much insolation Earth reflects back to space. Snow and ice bounce the sun's rays back into space far more effectively than unfrozen ocean or ice-free land. When temperatures are cold enough for snow cover to last through a summer season, the planet absorbs much less of the energy available in sunshine than it would without a covering of snow. Thus, as the ice expands, less solar energy is absorbed, which tends to cool the climate further and leads to further expansion of the ice cover. This ice-albedo feedback process can make the climate more sensitive to outside influences like shifting insolation.

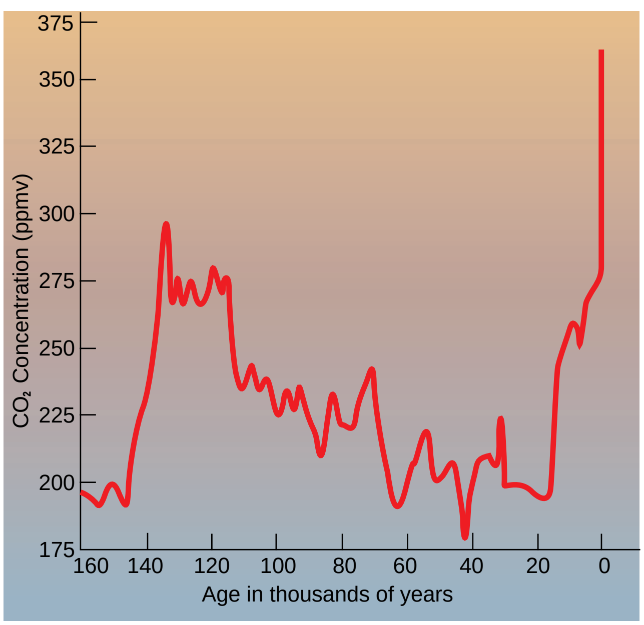
An important clue to understanding how the climate can get cold enough to sustain summertime snow comes from measurements of carbon dioxide (CO_2) gas, whose presence in the atmosphere tends to warm the climate, as explained on p. 14. Scientists can determine how much CO_2 existed in ancient air because some of that air is trapped in bubbles inside cores of ice from the Greenland and Antarctic ice sheets. These cores show that the atmosphere contained 40% less CO_2 when the ice reached its maximum extent 20,000 years ago than it did just prior to the Industrial Revolution in the 18th century. Estimates suggest that the reduced CO_2 may account for nearly half of the approximately 10˚F global cooling during this glacial maximum.

The discovery that variations in the chemical composition of the atmosphere are important

for explaining the ice ages has caused scientists to broaden their view of the climate system to include not only the physical processes that constrain energy and moisture, but also the chemical and biological processes that control atmospheric composition and land surface characteristics. Over the longer time spans required for major glacial cycles, the atmospheric CO_2 content is closely tied to the amount of CO_2 in the ocean. The amount of CO_2 in the ocean is dependent on marine organisms that use CO_2, sunlight, and nutrients in the process of photosynthesis. Lowered atmospheric CO_2 may have resulted from increased productivity of these marine organisms during the ice age.

Some things cause climate to change over periods shorter than glacial cycles. Climate change could, for example, be produced by variations in the energy output of the sun. Observations taken over the last few decades indicate that output is about 0.1% greater when the number of dark spots on the sun is at its maximum—roughly every 11 years—than when it is at a minimum. This change in energy output is too small to cause important climate variations, but the sun's output may vary more on longer time scales. Some evidence suggests that weakened solar energy output may have helped produce the Little Ice Age of 1350-1850AD. During this period cold spells were more common and temperatures were a few degrees colder than now in middle latitudes. But while mountain glaciers expanded in some regions, major ice sheets did not form.

Volcanic eruptions can affect the climate over the short term by sending large amounts of sulfur dioxide (SO_2) gas into the stratosphere, about ten miles above Earth's surface. In the stratosphere the SO_2 gas is converted into tiny sulfuric acid droplets that remain there for a year or more. These droplets reflect sunlight and reduce the solar heating of the planet. The eruption of Mt. Pinatubo in June of 1991 cooled the climate by a few tenths of a degree for about a year. But such effects fade as the volcanic



Past and Present Atmospheric CO_2 Concentration
Estimates of past carbon dioxide concentrations derived from ice cores drilled at Vostok in Antarctica and Siple Station in Greenland are combined with the modern instrumental record from Mauna Loa Observatory to create a continuous record that shows both natural changes associated with ice ages and the modern increase in CO_2 associated with human activities. Natural control of atmospheric CO_2 ended at the time of the Industrial Revolution, when humans began burning fossil carbon fuels, manufacturing cement, and removing forests at an increasing rate.

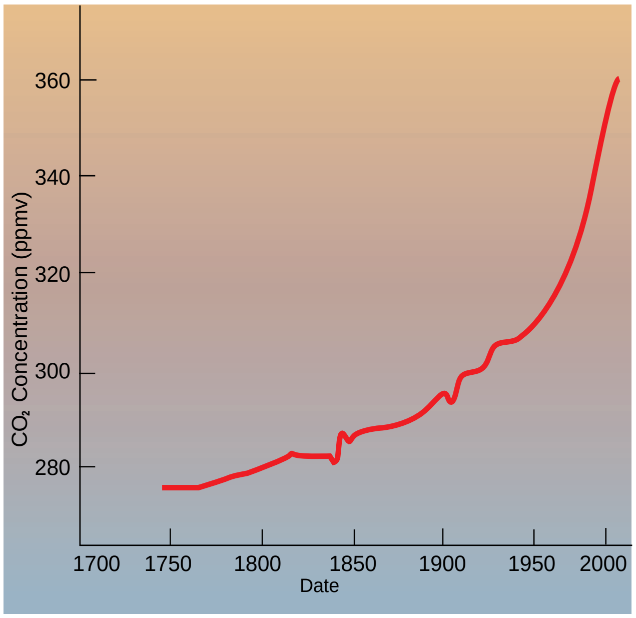
particles slowly fall out of the stratosphere. Only a succession of major volcanic eruptions could cause a longer-lasting change in climate.

Can We Change the Climate?

At the end of the last ice age, there were perhaps a million people in North America, or about one for every 7 square miles. Today, excluding Alaska and Hawaii, there are about 80 people for every square mile of land area in the United States. To sustain this population growth and raise our standard of living, we employ natural resources and technologies that were unknown to our ice age predecessors.

Human activities are leading to a buildup of certain trace gases in Earth's atmosphere. Measurements show that the level of carbon dioxide has increased by about 30% since the late 1700s. That time coincides with the beginning of the Industrial Revolution when the use of coal as an energy source began to increase rapidly. Burning coal releases CO_2 to the atmosphere. Other fossil carbon fuels, like petroleum and natural gas, also release CO_2 when they are burned. Such fuels are used in electrical generation plants, automobiles, home heating, and in a variety of other ways. Carbon dioxide also escapes to the atmosphere during the process of cement manufacture and as a result of the destruction of forests.

Atmospheric CO_2 has been increasing more rapidly in recent times, and continued growth of both population and per capita energy use will make it rise even faster in the 21st century. In addition, the levels of other trace gases in the atmosphere have increased during the industrial age, in most cases as a direct result of human activities. These include halocarbons, methane (CH_4), nitrous oxide (N_2O), and tropospheric ozone (O_3). In 1896, the Nobel Prize-winning Swedish chemist Svante Arrhenius predicted that the buildup of CO_2 in the atmosphere would warm the global climate. How can such a small change in atmospheric composition have such a big effect on climate?



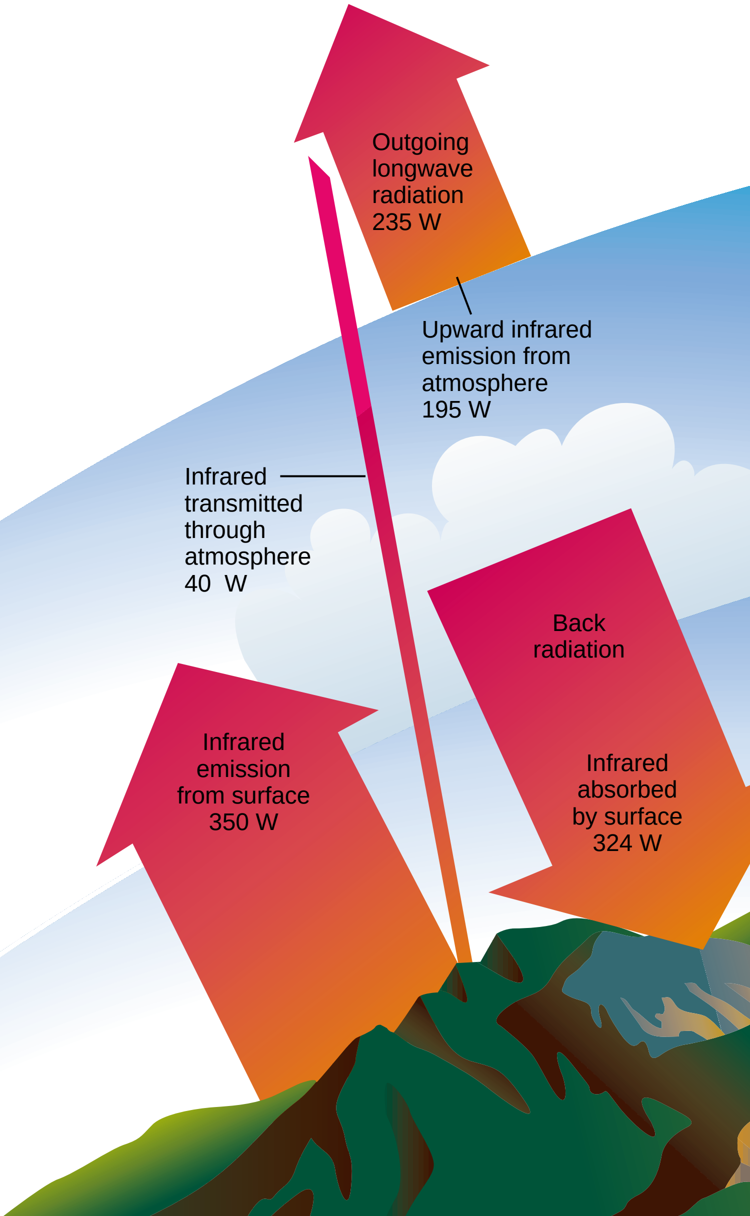
Atmospheric Carbon Dioxide Since Preindustrial Times
Atmospheric carbon dioxide has increased from a value of about 275 parts per million before the Industrial Revolution to about 360 parts per million in 1996, and the rate of increase has speeded up over this span of time. It is certain that the predominant cause of this increase is burning of fossil carbon fuels such as coal, oil, and natural gas. The amount of CO_2 in the atmosphere has been measured with instruments since 1957. CO_2 concentrations prior to 1957 are estimated from CO_2 amounts trapped in bubbles in ice cores from Greenland and Antarctica.

Without the greenhouse effect, Earth would be a frozen planet.

The Greenhouse Effect

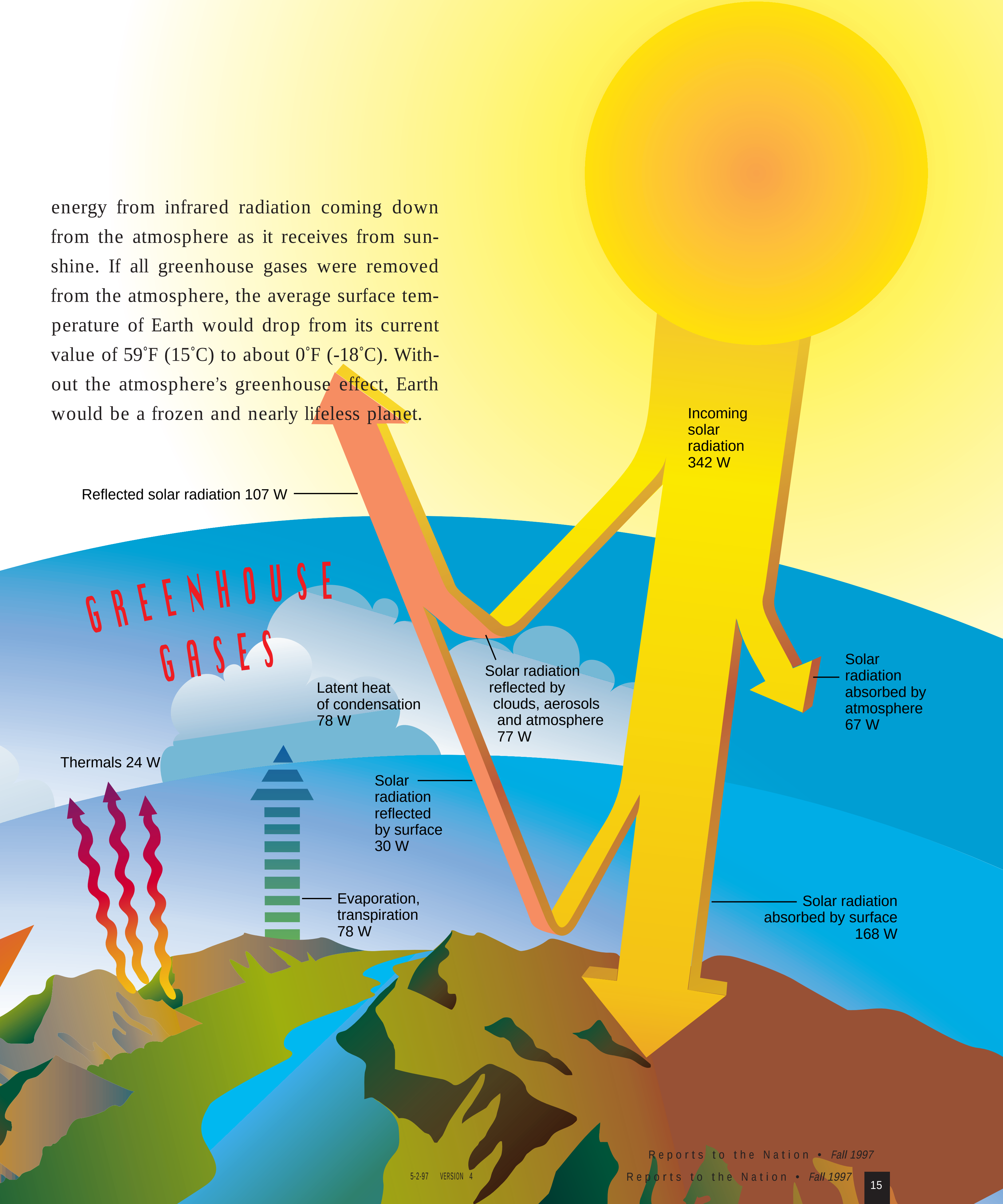
Carbon dioxide gas constitutes a tiny fraction of the atmosphere. Only about one air molecule in three thousand is CO_2. Yet despite their small numbers, CO_2 molecules can have a big effect on the climate. To understand why they are so important, we need to know about the greenhouse effect of the atmosphere. Earth's atmosphere lets in rays of sunshine and they warm the surface. The planet keeps cool by emitting heat back into space in the form of infrared radiation—the same radiation that warms us when we sit near a campfire or stove. But while the atmosphere is fairly transparent to sunshine, it is almost opaque to infrared radiation. Much like a garden greenhouse, it traps the heat inside.

About half of the solar energy that reaches Earth passes through the atmosphere and is absorbed at the surface. In contrast, about 90% of the infrared radiation emitted by the surface is absorbed by the atmosphere before it can escape to space. In addition, greenhouse gases like CO_2 as well as clouds can re-emit this radiation, sending it back toward the ground. The fact is, Earth's surface receives almost twice as much



The Greenhouse Effect
The atmosphere allows solar radiation to enter the climate system relatively easily, but absorbs the infrared radiation emitted by the Earth's surface. Although about half of the energy coming from the sun is absorbed at the surface of the Earth, almost twice as much surface heating is provided by downward infrared emission from the atmosphere as from sunshine. This "greenhouse effect" causes the surface of Earth to be much warmer than it would be without the atmosphere. The graphic on this page shows the flow of solar (yellow) and infrared (red) radiative energy through the climate system in watts per square meter of surface area. On average, 168 watts of solar radiation energy reach each square meter of the surface area, but the heating of the surface from the downward infrared radiation emitted by the atmosphere is almost twice that, 324 watts per square meter.

energy from infrared radiation coming down from the atmosphere as it receives from sunshine. If all greenhouse gases were removed from the atmosphere, the average surface temperature of Earth would drop from its current value of 59˚F (15˚C) to about 0˚F (-18˚C). Without the atmosphere's greenhouse effect, Earth would be a frozen and nearly lifeless planet.



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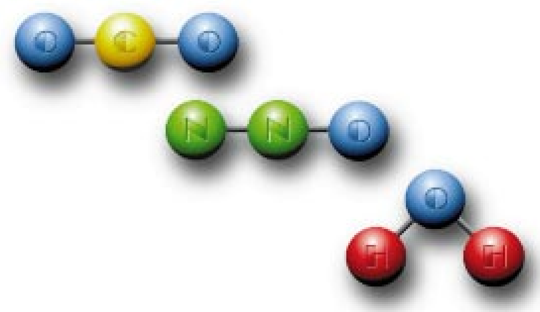
Denali National Park, Alaska.

It is the distinctive molecular structures of the greenhouse gases that make them strong absorbers and emitters of infrared radiation. About 99% of air molecules are nitrogen and oxygen, which have a simple structure consisting of two identical atoms. Because of this simple structure, they have a relatively minor effect on the transmission of solar and infrared radiation through the atmosphere. Molecules with three or more atoms like water vapor, carbon dioxide, ozone, and a host of other trace gases can efficiently absorb and emit infrared energy by storing and releasing it in molecular vibration and rotation. Though some of these gases constitute only a tiny fraction of the atmosphere, they can nevertheless make significant contributions to the greenhouse effect.

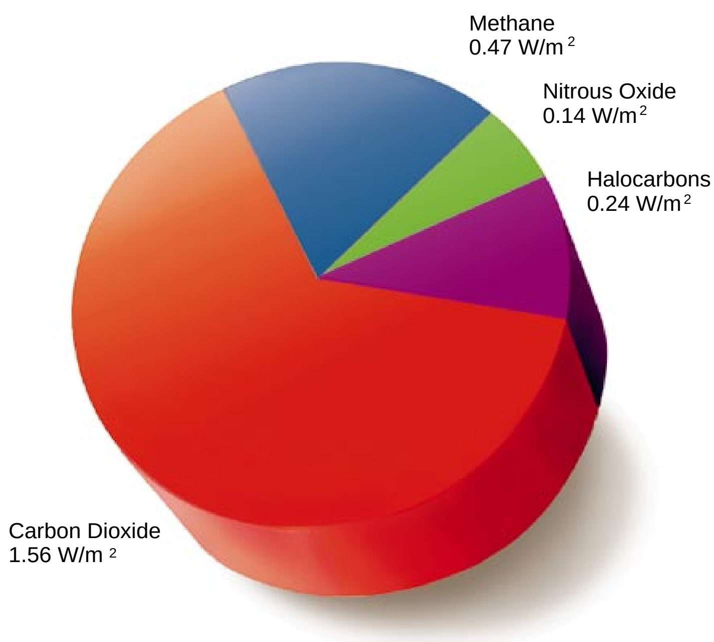
The molecule that makes the largest contribution is water vapor, which is a relatively abundant greenhouse gas. An average water molecule stays in the atmosphere only a few days from the time it evaporates from the surface to the time it falls out of the atmosphere as precipitation, so the water vapor content of the atmosphere adjusts quickly to changes in surface temperature. Humanity can do little to directly control the global amount of atmospheric water vapor. Because atmospheric water vapor tends to increase with increasing temperature, however, it can amplify climate changes produced by other means—a process called water vapor feedback.



Why Are Greenhouse Gas Amounts Increasing?

Carbon dioxide has a much longer lifetime in the atmosphere than water vapor. If CO_2 is suddenly added to the atmosphere, it takes 100 to 200 years for the amount of atmospheric CO_2 to establish a new balance, compared to several weeks for water vapor. That's because the carbon in CO_2 is cycled between the atmosphere and the ocean or land surface by slow chemical and biological processes. Plants, for example, use CO_2 to produce energy in a process known as photosynthesis. Through millions of years of Earth's history, trillions of tons of carbon were taken out of the atmosphere by plants and buried in sediments that eventually became coal, oil, or natural gas deposits. In the last two centuries humans have used these deposits at an increasing rate as an economical energy source. In a similar way, cement manufacture releases carbon atoms buried in carbonate rocks. Today humanity releases about 5.5 billion tons of carbon to the atmosphere every year through fossil fuel burning and cement manufacture. Approximately another 1.5 billion tons per year are released through land use changes such as deforestation. These releases result in an increase of atmospheric CO_2 of about one-half percent per year.

Other naturally occurring greenhouse gases such as methane and nitrous oxide have also been increasing, and entirely man-made greenhouse gases such as halocarbons have been introduced into the atmosphere. Many of these gases are increasing more rapidly than carbon dioxide. The amount of methane, or natural gas, in the atmosphere has doubled since the Industrial Revolution. Although its sources are many, the increase is believed to come mainly from rice paddies, domestic animals, and leakage from coal, petroleum, and natural gas mining. Halocarbons are a family of industrial gases that are manufactured for use in refrigeration units, as cleaning solvents, and in the production of insulating foams. They were first manufactured in the 1940s, and because they do not readily react with other chemicals



Climate Forcing by Greenhouse Gas Increases Since the Industrial Revolution. Changes in the atmospheric concentration of CO_2, methane, nitrous oxide, and halocarbons that have occurred since the Industrial Revolution have altered the energy budget of Earth. The difference is about 2.4 watts per square meter, or roughly 1% of the energy flow through the global climate system.

they can have a lifetime in the atmosphere of more than 100 years. Halocarbons are also responsible for the Antarctic ozone hole and a more general decline in global stratospheric ozone, but this is a separate problem from the greenhouse warming contributed by the halocarbons. Production of some of the halocarbons that are important greenhouse gases has been regulated by international agreements to preserve Earth's protective ozone layer, so their influence on climate should decline in the future. Nearer to Earth's surface, in the troposphere, ozone amounts have been increasing because of human activities. Ozone at the surface has harmful effects on the health of plants, animals, and humans.

Aerosols: Sunscreen for the Planet?

Although raising the levels of greenhouse gases in the atmosphere is our most important direct influence on the global climate, human actions also contribute to the aerosol content of the atmosphere. Aerosols are tiny particles of liquid or solid matter that are suspended in air. They are different from water cloud droplets or ice particles in that they are present even in relatively dry air. Atmospheric aerosols have many sources and are composed of many different materials including sea salt, soil, smoke, and sulfuric acid. Although aerosols have many natural sources, it is estimated that aerosols resulting from human activities are now almost as important for climate as naturally produced ones. Most of the human-induced aerosols come from sulfur released in fossil fuel burning and from burning vegetation to clear agricultural land. Human production of sulfur gases accelerated rapidly in the 1950s.

It appears that the cooling effect of aerosols has canceled out part of the warming that might have been associated with recent greenhouse gas increases. Aerosols can reflect solar radiation or absorb and emit infrared radiation, and are often visible as haze or smog. By reflecting sunlight, they cool the climate. The human-induced increase in atmospheric aerosols since preindustrial times is believed to have reduced the energy absorbed by the planet by about half a watt per square meter, enough to offset about 20% of the greenhouse gas warming effect.

The aerosols produced by humans could also have a significant effect on the amount or properties of clouds. Every cloud droplet or ice particle has at its center an aerosol called a cloud condensation nucleus, on which the water vapor collected to form the cloud droplet. Aerosols that attract water, such as those composed of salt or sulfuric acid, are particularly effective as cloud condensation nuclei. The increased number of aerosols produced by humans could cause the water in clouds to be distributed into more, but smaller, cloud droplets. With their water spread more diffusely, the clouds would reflect more solar radiation. The existence of such clouds would cause a cooling that might offset part of the greenhouse gas warming, but the size of this effect is very uncertain.

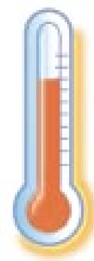
We must keep in mind some very important differences between the greenhouse warming and the aerosol cooling. While greenhouse gases such as CO_2 and halocarbons remain in the atmosphere for about a century after being released, aerosols released into the lower atmosphere remain there only a few weeks. Therefore human-produced aerosols are not distributed evenly over the globe, but tend to be concentrated near the points where they are released into the atmosphere. Most of them originate in industrialized countries of the Northern Hemisphere, where fossil fuels are burned, and in land areas where vegetation is burned. Because their effects are more localized, aerosols may cause regional shifts in climate. Also, because of their short lifetimes in the atmosphere, the effect of aerosols on today's climate is determined by the amount of aerosol produced during the previous couple of weeks. In contrast, the CO_2 that we release into the atmosphere today will affect the climate for more than 100 years.

For these reasons the greenhouse gas warming must eventually overwhelm any human-induced aerosol cooling that may be taking place. Nonetheless it is important to understand the effect of aerosols on the climate so that we may better predict how changing greenhouse gas amounts will affect the future climate and assign the proper causes to temperature changes when we observe them. Efforts are underway to reduce the release of SO_2 gas from coal-fired energy plants because it causes acid rain and lung disease, and this may have the effect of reducing aerosol amounts in some regions.

How Has Climate Changed in the Past Century?

Measurements indicate that global mean surface temperature has increased by about 1˚F (0.5°C) in the past century. The warming has been greatest over the continents between 40 and 70 degrees North latitude. Over this same period of time global sea level has risen between 4 and 10 inches (10-25 cm). Scientists do not yet know with certainty what part of these changes is caused by human activities and what part would have occurred anyway. Part of this warming may be a rebound from the cooling of the Little Ice Age during the 1350-1850 period, which was probably unrelated to human activities. But this warming also happened during the period when human activities were increasing CO_2 and other greenhouse gas amounts in the atmosphere. Many scientists are convinced that human activities have made a major contribution to the warming of the past century, and that warming caused by greenhouse gas increases will be a continuing part of our future.

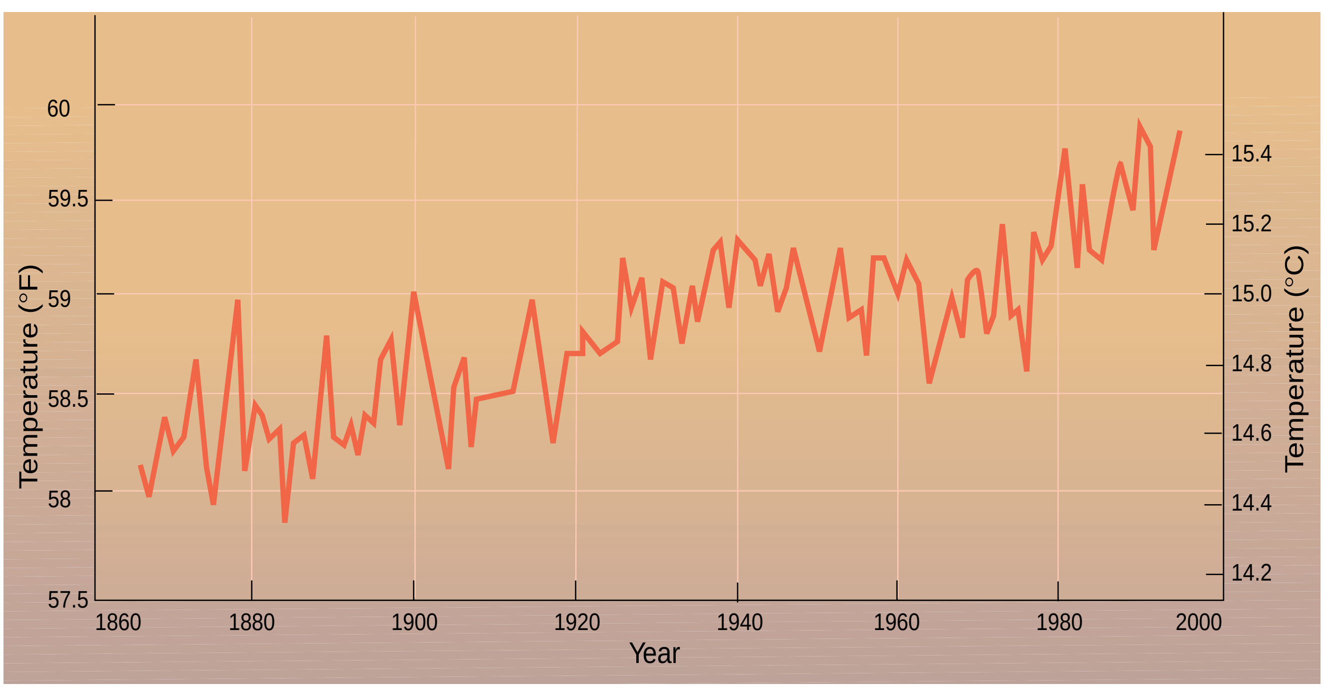
A rapid greenhouse warming of the climate



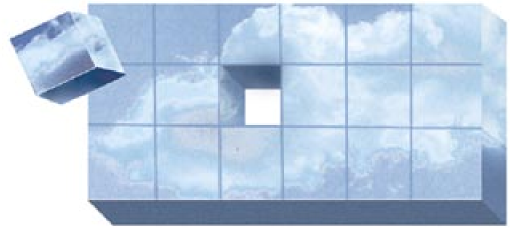
would cause serious problems. Because such a warming, once initiated, would last for a long time, scientists and civic planners are very interested in knowing how much warming is occurring and what part of it can be attributed to human actions. The record of global temperature obtained from thermometers around the world extends back in time only a little over a century. This record shows a steady increase up until 1940, followed by a period of slight cooling. Since the 1970s the temperatures have gone up rapidly, and many of the warmest years in the global temperature record have occurred in the past 15 years. It is not known with certainty whether this recent warming trend will continue, or whether it is caused by the increasing trend of greenhouse gas concentrations in the atmosphere. The natural random variability of the climate system on decade-long time scales is fairly large, and it is not yet clear how to separate this variability from changes that have resulted from human activities.

Can We Predict Climate Change?

The behavior of the climate system can be simulated with computer models, and the simulations can then be tested against observations of current and past climate. They can be used to study the response of the climate to changing amounts of greenhouse gases and



Instrumental Temperature Record 1865-1995
The record of global mean surface air temperature from thermometer readings indicates a global warming over the past century, with many peaks and troughs suggesting the natural year-to-year variability of climate.



aerosols, to changes in land surface conditions, and to other natural or human-caused changes. But while such models capture many of the key features of the present climate, they do have shortcomings.

Modeling the climate on a computer is difficult because processes with very large spatial scales, such as the transport of energy from the tropics to the poles by atmospheric motions, are just as important as small-scale processes like the collection of water molecules into raindrops. How do we represent this wide range of spatial scales in a single model that is efficient enough to run on available computers in a reasonable length of time? The standard approach is to represent the globe with a grid of boxes about 100 miles on a side and then predict the average properties in these boxes using known laws of physics. The effects of processes that occur on smaller scales are represented with approximate formulas that relate them to the averaged properties in the grid boxes. The problem with this approach is that some of the small-scale processes that must be treated in a more approximate fashion are also central to the feedback effects that determine how much climate change will result from human actions. For example, clouds have a huge influence on the transmission of solar and infrared radiation through the atmosphere, yet the processes that determine the properties of clouds occur on scales that are much smaller than a climate model grid box. A large part of the uncertainty in forecasts of future climates derives from uncertainty about how to treat clouds in climate models. Important feedbacks such as those involving surface ice and atmospheric water vapor also involve processes occurring on small scales that must be treated with approximate formulas. As computer power and understanding both increase, some of the uncertainty associated with feedback processes will decline and more accurate climate forecasts will become available.

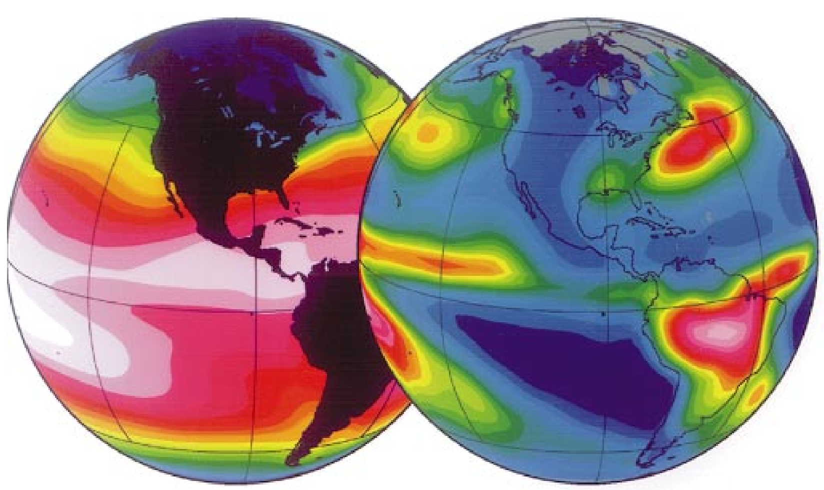
What Do Climate Models Tell Us About Our Future?

Once a climate model has been tested against current and past observations, it is reasonable to ask what it can tell us about future climates. A typical experiment of this nature is to extend the 20th century's increase in greenhouse gases into the next century and see how the climate model responds to this change. Because of the approximations in the models, however, the projected warming over the next century is quite uncertain, ranging from a modest warming of 2˚F (1˚C) to a very substantial warming of 8˚F (4.5˚C). Models consistently predict that the warming would be greater in high latitudes than in the tropics, and greater over land than ocean. Many models predict larger increases in evaporation than in precipitation over midlatitude land areas, which would result in drier conditions in those regions, especially during summer in North America and Southern Europe. Warming may cause agricultural zones in North America to move northward, which would benefit some communities and harm others. Changes in the climate of specific small regions and changes in the activity of tropical storms cannot yet be predicted with much confidence. When natural climate fluctuations cause sea surface temperature in the tropical North Atlantic to increase, hurricane activity also seems to increase, but it is not certain that a global surface temperature rise caused by greenhouse gas increases would have a proportional effect on hurricane activity.

The effect of the warming on humanity depends on the magnitude of the warming, the speed with which the warming occurs, and the way society organizes itself to adapt to climate change. If the warming is as fast and as large as some of the models suggest, then the effects on people and our natural environment could be quite serious. Agriculture and water supplies can take decades to adapt, and natural ecosystems take centuries. Therefore, a more rapid change would pose more difficult problems.

Where Do We Go From Here?

When planning for the future, we often assume that the climate we have experienced in the past will continue, but this may not be the case. Rain, snow, and temperature affect many aspects of human life, including public health, agriculture and the way we manage our water and energy resources. We know that the amounts of some greenhouse gases in the atmosphere are increasing as a result of human activities. The well-understood physics of the greenhouse effect indicates that the changing composition of the atmosphere should warm the surface climate of Earth. Current estimates of the expected

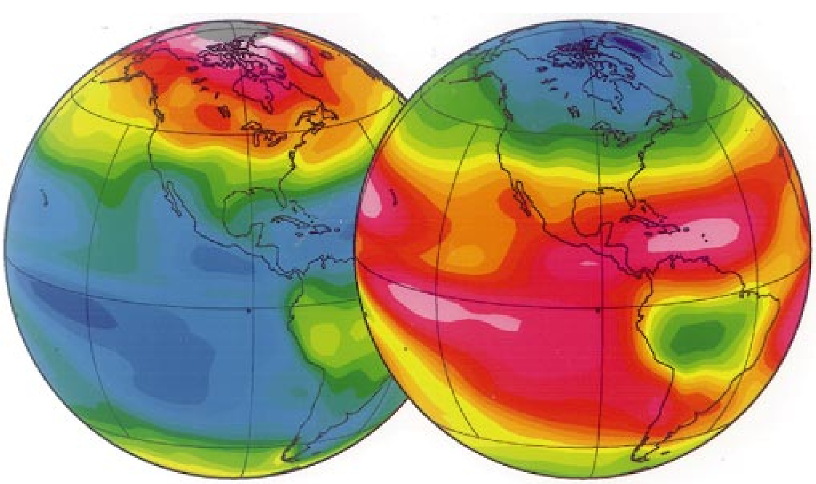


Images of Earth
Climatological values for the December through February season of (from left to right): sea surface temperature, rainfall, albedo, and outgoing infrared emission. Values range from low to high as the color goes from blue to red to white. The heavy precipitation over South America during this season is accompanied by the high albedos and low infrared emission associated with tall convective clouds.

climate change over the next century range from a future climate modestly warmer than today to one warmer than any that has occurred on Earth for more than a million years. This range of uncertainty is uncomfortably large. Moreover, current models cannot make accurate predictions of how temperature and the availability of water might change in a particular state or county, where measures to adapt to climate change would need to be taken.

Scientists are working hard to improve our understanding of the climate system and our ability to predict its future course. This work involves taking careful observations to monitor subtle changes in the climate system, conducting intensive observational programs to study the processes that determine how much climate change to expect, and continuing to improve climate models and test them against observations. We also need to improve our knowledge of the two-way relationship between humans and climate. Because of the long lifetime of greenhouse gases in the atmosphere, decisions that are made during the next decade or so could affect the quality of life for generations to come.

Given the current level of uncertainty and the complexity of the climate system, the future will likely bring surprises, which could be of either the pleasant or the unpleasant variety. Information about how the climate is changing, knowledge of why observed changes occur, and accurate prediction of future climates will be very important for the public and policy makers. Efficient communication of this information to all concerned will be an important part of the process of deciding how to respond to the challenge of our changing climate.



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Humanity, long affected

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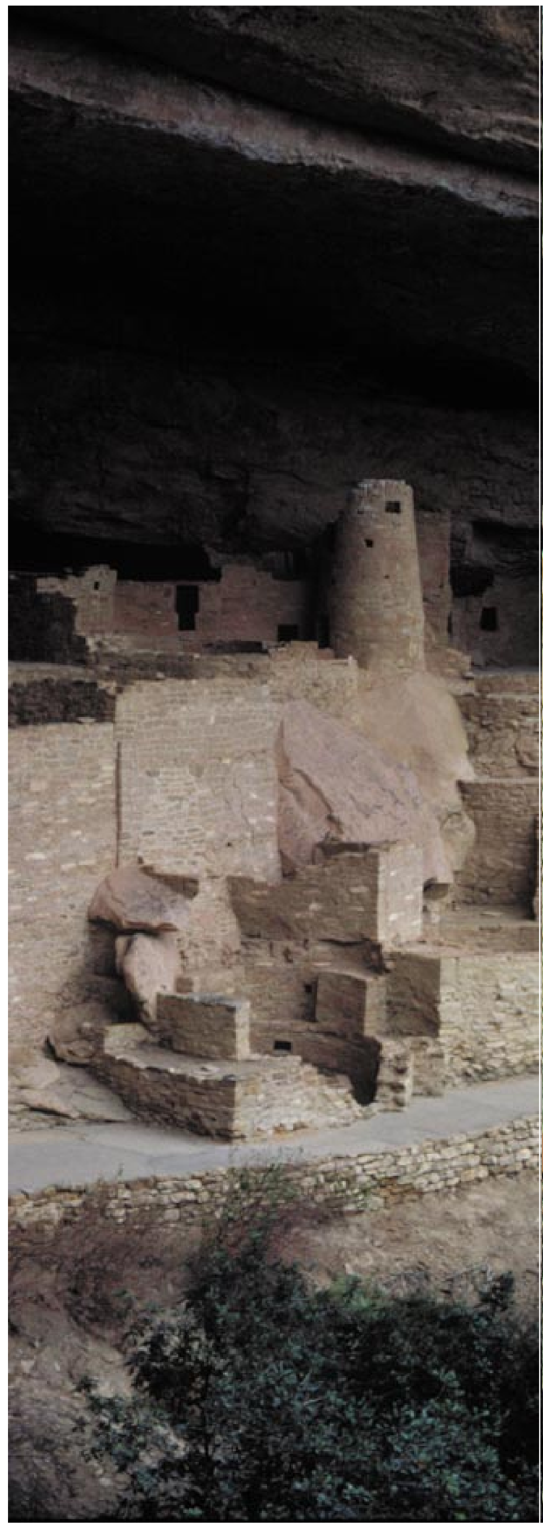

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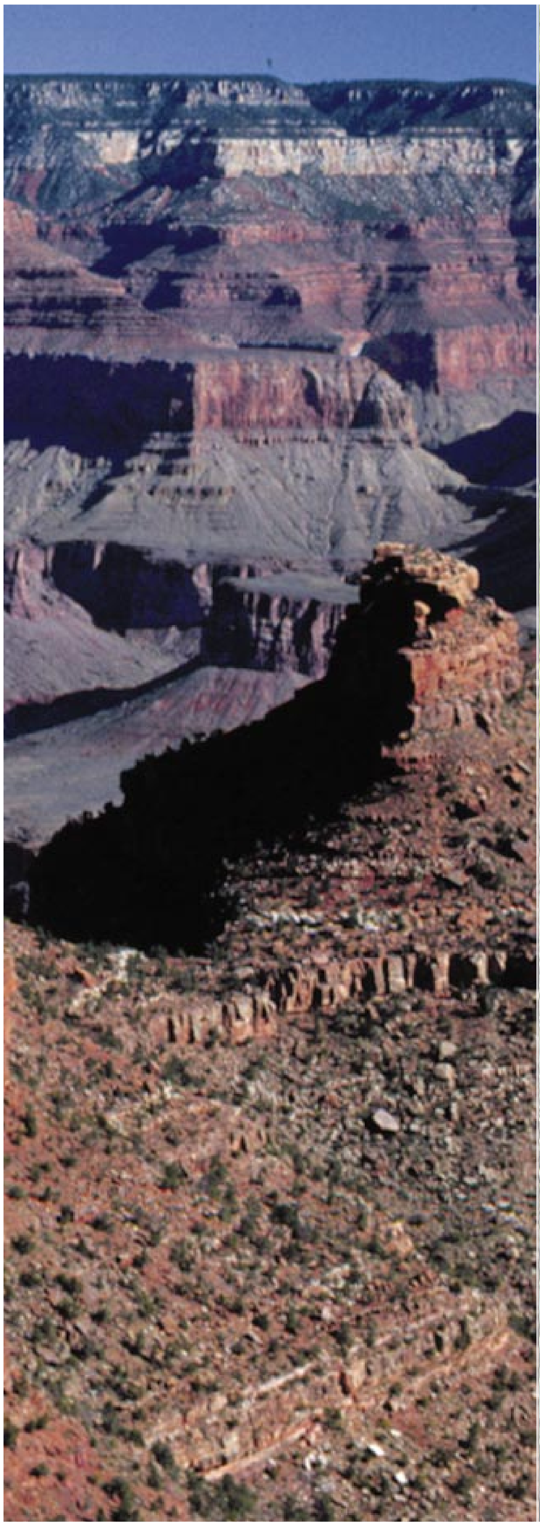

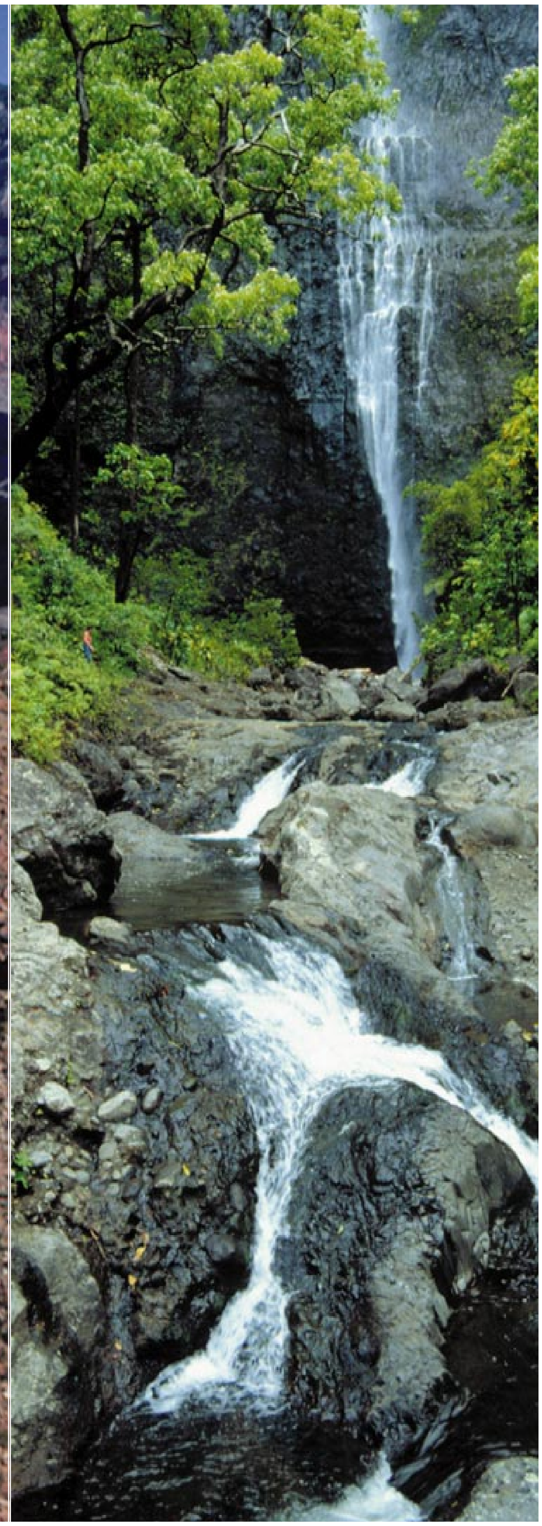

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