Chapter 8:
Climate of the Southwestern US

Climate is a description of the average temperature, range of temperatures, humidity, precipitation, and other **atmospheric**/hydrospheric conditions a region experiences over a period of many years. These factors interact with and are influenced by other parts of the Earth **system**, including geology, geography, insolation, currents, and living things.

Because it is founded on statistics, climate can be a difficult concept to grasp, yet concrete examples can be illuminating. Terms like "desert," "rain forest," and "tundra" describe climates, and we have gained a general understanding of their meaning. Climate can also encompass the cyclical variations a region experiences; a region with a small temperature variation between winter and summer—San Francisco, for example—has a different climate from one that has a large variation, such as Buffalo. Scientists have settled on 30 years as the shortest amount of time over which climate can be defined, but it can of course also define time periods millions of years in length.

You cannot go outside and observe climate. **Weather**, on the other hand, can be observed instantly—it is 57 degrees and raining *right now*. Weather varies with the time of day, the season, multi-year cycles, etc., while climate encompasses those variations. Our choice of clothing in the morning is based on the weather, while the wardrobe in our closet is a reflection of climate. Due to the area's great regional variety, from the arid zones of the Basin and Range to the higher, wetter parts of the Rocky Mountains, residents of the Southwest have a diverse wardrobe. While the entire Southwest experiences seasonal variation, southernmost Arizona and New Mexico experience much less variation due to the warmth of their winters.

Past Climates

Climate, like other parts of the Earth system, is not static but changes over time, on both human and **geologic time scales**. Latitude, for example, has a very direct effect on climate, so as the continents shift over geologic time, the climates on them also shift. Furthermore, the conditions on Earth as a whole have varied through time, altering what kinds of climates are possible. Throughout most of its long history, the Southwest has been tropical or temperate, but it has also ranged from very wet to very dry.

Ancient climates are reconstructed through many methods. Written records and **tree** rings go back hundreds of years, **glacial** ice cores hundreds of thousands of years, and **fossils** and rocks that indicate different climates go back hundreds of millions of years. These clues, coupled with modeling and a knowledge of physics and chemistry, help climatologists put together an increasingly detailed history of the Earth's climate, and of that of the Southwest. Unfortunately, we do not have as clear an understanding of climate for the earliest part of Earth

atmosphere • *a layer of gases surrounding a planet.*

system • *a set of connected things or parts forming a complex whole.*

weather • *the measure of short-term conditions of the atmosphere such as temperature, wind speed, and humidity.*

geologic time scale • *a standard timeline used to describe the age of rocks and fossils, and the events that formed them.*

glacier • *a body of dense ice on land that does not melt away annually and has sufficient mass to move under its own weight.*

fossil • *preserved evidence of ancient life.*

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history as we do for the later parts, because the oldest rocks are much more difficult to find. However, we can still say something about the climate of the ancient Earth, in large part due to our knowledge of atmospheric chemistry.

Ancient Atmosphere

Not long after the Earth first formed, more than 4.5 billion years ago, its atmosphere was composed mostly of hydrogen and **helium**. **Volcanic** activity and collisions with **meteorites** and comets added water vapor, carbon dioxide (CO_2), and nitrogen to the atmosphere. As the Earth cooled enough for liquid water to form, the vapor formed clouds from which the rain poured forth in such a deluge as the planet will never experience again. These torrential rains were constant for *millions* of years, absorbing **salt** and other **minerals** from the earth as the rainwater coursed to the lowest areas, forming Earth's oceans and seas.

At this time, the sun produced significantly less **energy** than it does today, so one might expect that once the oceans formed, they would continue to cool and eventually freeze. Yet temperatures stabilized, perhaps because there was a greater concentration of potent **greenhouse gases** in the atmosphere and less land surface to reflect light, so temperatures remained high enough for liquid water to exist. Indirectly, the ocean was responsible for the final ingredient of the modern atmosphere because it was home to the first life on Earth. Photosynthetic bacteria appeared perhaps as early as 3.5 billion years ago, but abundant **iron** and organic matter quickly absorbed the oxygen they produced. After hundreds of millions of years, these sinks were filled, and free oxygen could finally build up in the atmosphere. With this addition, the modern atmosphere was complete, though the relative amounts of the gases composing it would, and still continue to, shift. *The composition of the atmosphere and the huge volume of water on Earth are two of the most important factors affecting climate.*

Much of the light from the sun passes unimpeded through the atmosphere and hits the Earth. Approximately 70% of that light is absorbed and retransmitted from the surface as heat. The transmitted heat, which has a longer wavelength than light, is trapped by gases in the atmosphere including water vapor, carbon dioxide, and methane. The similarity between this process and that which warms a greenhouse earned these "greenhouse gases" their moniker.

While the atmosphere was forming about 3.7 billion years ago, the surface of the Earth was cooling to form a solid **crust** of rock (although there are indications that this process may have started as early as 4.4 billion years ago). Regardless of precisely when this took place, it represented the beginning of tectonic processes that have continued ever since. Molten rock from the **mantle** constantly wells up from deep fissures and solidifies into relatively **dense** rock, while more buoyant rock floats higher on the **magma** and is pushed around on the slow conveyor belts of mantle-formed rock (*Figure 8.1*). Denser rock forms

helium • *a gaseous chemical element (He), which is the second most abundant and second lightest element in the universe.*

volcanism • *the eruption of molten rock onto the surface of the crust.*

meteorite • *a stony or metallic mass of matter that has fallen to the Earth's surface from outer space.*

salt • *a mineral composed primarily of sodium chloride (NaCl).*

mineral • *a naturally occurring solid with a specific chemical composition and crystalline structure.*

energy • *the power derived from the use of physical or chemical resources.*

greenhouse gas • *a gas in the atmosphere that absorbs and emits heat.*

iron • *a metallic chemical element (Fe).*

Past

oceanic **plates** that are lower and covered in water, and lighter rock forms continental plates, though part or all of a continental plate may be submerged under a shallow sea. The motion of these plates, the rearrangement of the continents, and the amount and types of minerals exposed to the atmosphere play a huge role in the climate. Not only do the continents and oceans move through different climate zones, but the continents also affect climate based on their size, and the **weathering** of rock on the continents plays a large role in the composition of the atmosphere. For example, rock that is enriched in organic matter will release abundant amounts of carbon dioxide as it weathers, while rock rich in **feldspar** and **mica** will take up carbon dioxide.

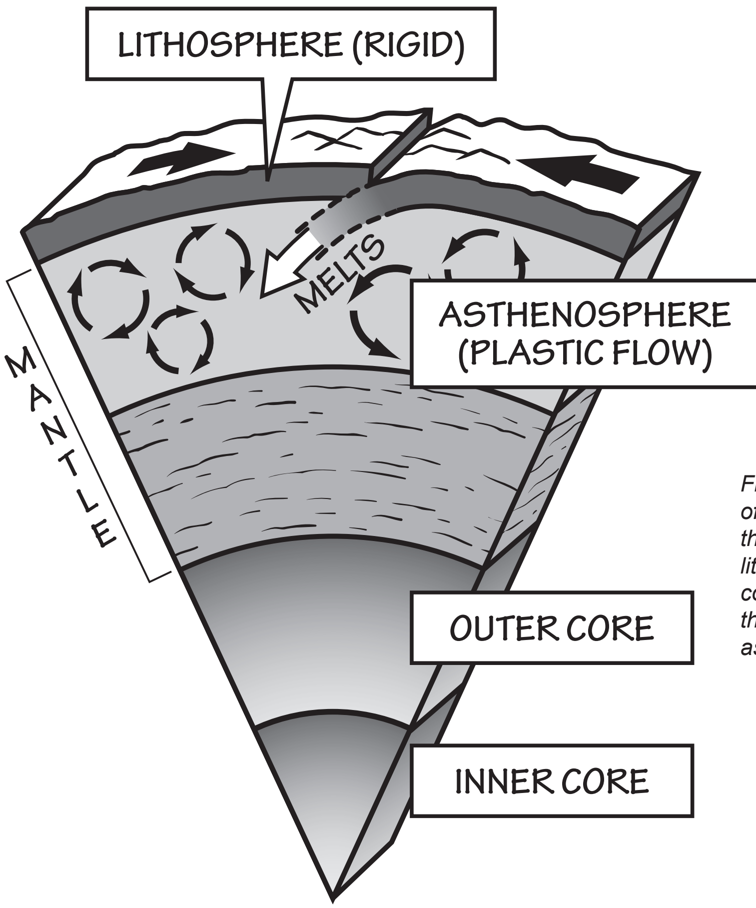

Figure 8.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Nearly one billion years ago, the Earth began fluctuating between warm and cool periods lasting roughly 150 million years each. During cool periods, there is usually persistent ice at the poles, while during warm periods there is little or no glaciation anywhere on Earth. Today, we are still in a cool period—although the world has been cooler than it is at present, it has been far hotter for much of its history (*Figure 8.2*). Through the shifting global climate and the movement of the continents, what is now the Southwest has at times been at the bottom of a shallow sea, a coastal plain with swamps and rivers, and even inundated by monsoonal rains or clouded by intense dust storms.

crust • *the uppermost, rigid outer layer of the Earth.*

mantle • *the layer of the Earth between the crust and core.*

density • *a physical property of minerals, describing the mineral's mass per volume.*

magma • *molten rock located below the surface of the Earth.*

plates • *large, rigid pieces of the Earth's crust and upper mantle, which move and interact with one another at their boundaries.*

weathering • *the breakdown of rocks by physical or chemical means.*

feldspar • *an extremely common group of rock-forming minerals found in igneous, metamorphic and sedimentary rocks.*

mica • *a large group of sheetlike silicate minerals.*

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Huronian glaciation • *a glaciation beginning about 2.4 billion years ago, that covered the entire surface of the Earth in ice for as long as 300 million years.*

plate tectonics • *the process by which the plates of the Earth's crust move and interact with one another at their boundaries.*

ice sheet • *a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

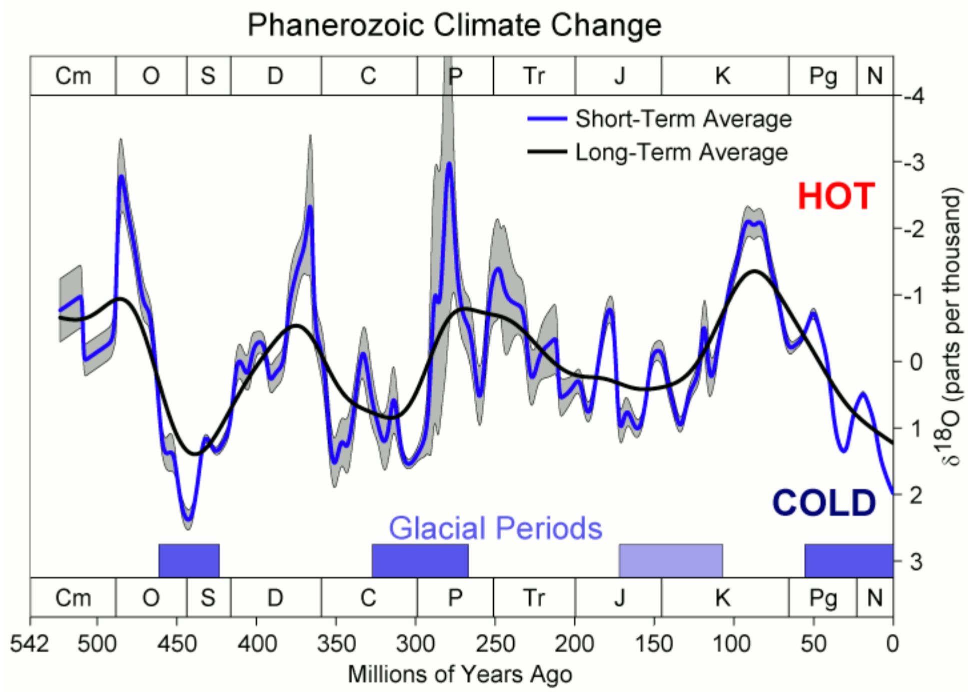

Figure 8.2: Changing global climate throughout the last 542 million years. These data were compiled using the ratios of stable oxygen isotopes found in ice cores and the carbonate skeletons of fossil organisms. (See TFG website for ful-color version.)

Snowball Earth

There is evidence suggesting that the entire surface of the planet has been covered in ice several times, a hypothesis called Snowball Earth (*Figure 8.3*). Glacial deposits discovered near Lake Huron and elsewhere show that starting about 2.4 billion years ago the entire surface of the Earth may have been covered in ice for as long as 300 million years, an event known in North America as the **Huronian glaciation**. At that time the continental plates made up less than half as much of the Earth's surface as they do today and were unified as the continent Arctica. It may have been early life's production of oxygen that reacted with and lowered the amount of the greenhouse gas methane in the atmosphere, tipping the Earth toward a series of cooling feedbacks and causing ice to spread from pole to pole.

An ice-covered planet would remain frozen because almost all of the sun's energy would be reflected back into space, but this did not happen on Earth because of **plate tectonics**—the Snowball Earth cycle was eventually disrupted by volcanic activity. While the Earth was covered in ice, volcanoes continued to erupt, dumping carbon dioxide and methane into the atmosphere. While these gases are usually removed from the atmosphere by organisms and the weathering of rocks, this was not possible through miles of ice! After millions of years, the concentrations of methane and CO_2 increased to the point that greenhouse warming began to melt the **ice sheets**. Once the melting started, more of the sun's energy was absorbed by the surface, and warming feedbacks began. Because the oceans had been covered, nutrients derived from volcanic

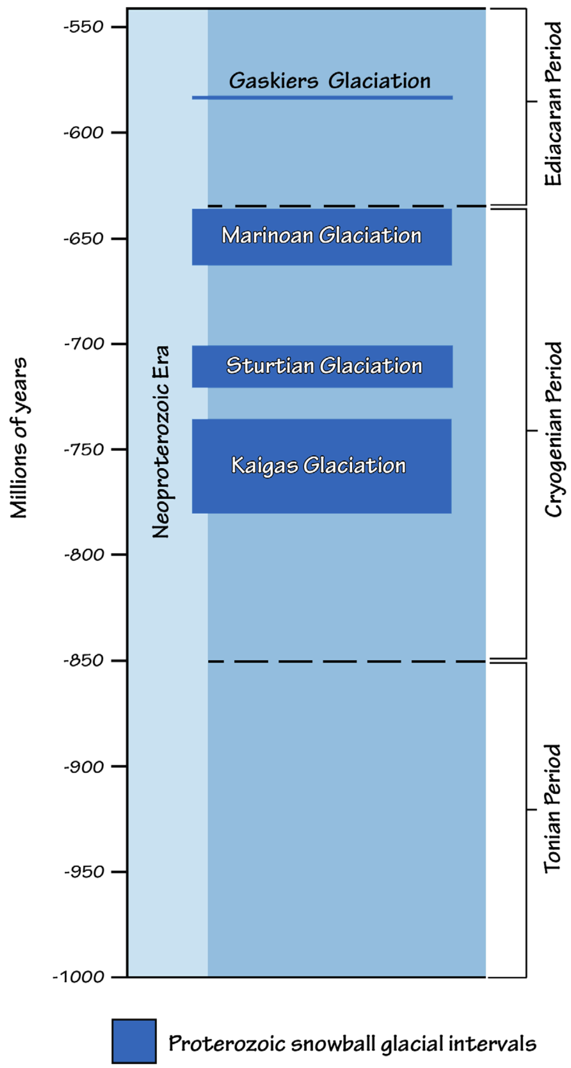

Figure 8.3: Snowball Earth periods during the Proterozoic.

gases and chemical changes in the rocks accumulated in the waters. Once they were re-exposed to light, a population explosion of **cyanobacteria** produced more and more oxygen, which was capable of combining with freshly thawed carbon sources to make more carbon dioxide, further enhancing the warming.

For the next 1.5 billion years, the Southwest, free of ice, drifted around the surface of the Earth. A new supercontinent—**Rodinia**—formed, and the part that is now North America was stable, creating what is known as a **craton**, or continental interior relatively free of the folding and **faulting** that characterizes continental margins that are subjected to mountain building and other plate tectonic processes. Since the Southwest was part of that craton, it was probably underwater for most of this time. About 850 million years ago, during the **Cryogenian**, the Earth entered a 200-million-year **ice age**, during which there were two more Snowball Earth cycles. Although the part of Rodinia that would eventually become North America was located near the equator, the fact that North America was at such a low latitude, yet had glaciers, is strong evidence

cyanobacteria • *a group of bacteria, also called "blue-green algae," that obtain their energy through photosynthesis.*

Rodinia • *a supercontinent that contained most or all of Earth's landmass, between 1.1 billion and 750 million years ago, during the Precambrian.*

craton • *the old, underlying portion of a continent that is geologically stable relative to surrounding areas.*

fault • *a fracture in the Earth's crust in which the rock on one side of the fracture moves measurably in relation to the rock on the other side.*

Cryogenian • *a geologic period lasting from 850 to 635 million years ago, during the Precambrian.*

ice age • *a period of global cooling of the Earth's surface and atmosphere, resulting in the presence or expansion of ice sheets and alpine glaciers.*

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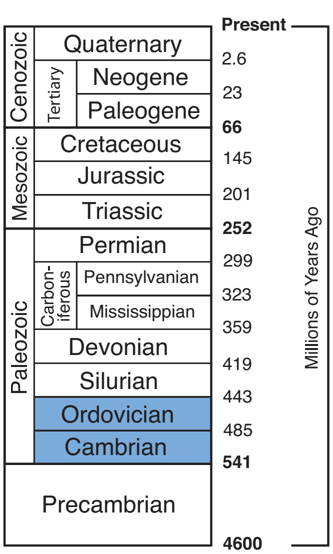
tillite *• glacial till that has been compacted and lithified into solid rock.*

Proterozoic *• a geologic time interval that extends from 2.5 billion to 541 million years ago.*

Paleozoic *• a geologic time interval that extends from 541 to 252 million years ago.*

mass extinction *• the extinction of a large percentage of the Earth's species over a relatively short span of geologic time.*

sandstone *• sedimentary rock formed by cementing together grains of sand.*



that the Earth really did freeze over completely. **Tillites**—rocks composed of ancient glacial sediment—found in Utah provide direct evidence for **Proterozoic** glaciation.

See Chapter 2: Rocks for more about the Proterozoic rocks of Utah.

Life and Climate

With the start of the **Paleozoic** era, climates across the world were warm, and North America was located in the low and warmer latitudes of the Southern Hemisphere. As the **Cambrian** progressed, North America moved northward, and what would become much of the Southwestern US was located near the Tropic of Capricorn (*Figure 8.4*). Shallow seas invaded the continent, ultimately covering the whole area until the late **Carboniferous**. During this time, the only exposed areas were islands in western Colorado and parts of New Mexico. Although there is a rich marine fossil record from the areas between these islands, we have no record of what kinds of plants colonized the land after land plants evolved in the late **Ordovician** and **Silurian**.

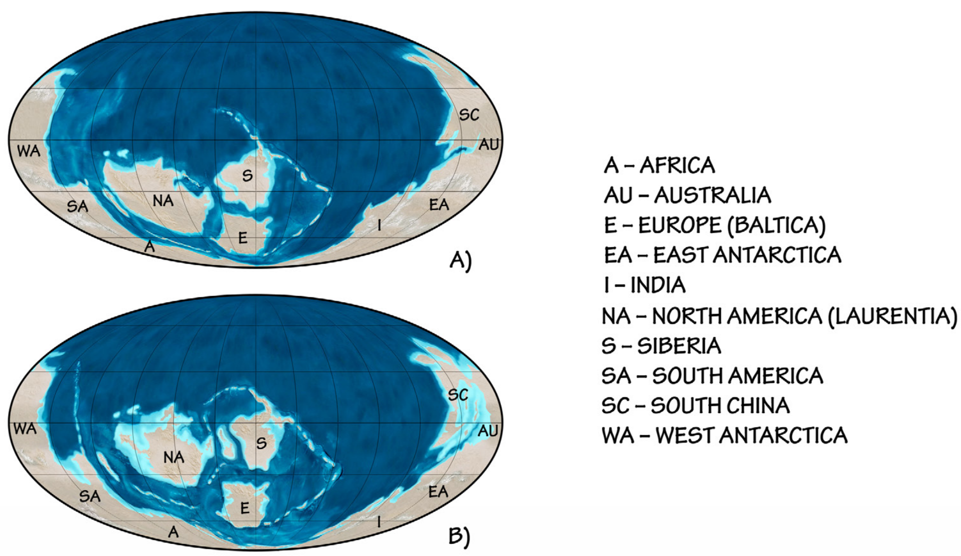


Figure 8.4: The location of the continents during the A) early and B) late Cambrian. Note the position of North America relative to the equator.

In the late Ordovician (about 460 to 430 million years ago), the Earth fell into another brief but intense ice age. Glaciers covered most of the world's southern landmasses, which were located over the South Pole. This led to global cooling, which was associated with the first of five major **mass extinctions** that have occurred over the last half-billion years. Although global sea level dropped during this event, North America's position near the equator kept its climate relatively warm. Ordovician deposits across the Southwest indicate warm, shallow seas rich in invertebrate life; shelly **sandstones** in Utah represent vast tidal flats.

Climate 8

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In the Silurian and **Devonian** (430 to 300 million years ago), North America moved north across the equator, and the cycle of warming and cooling was repeated yet again. Glaciation in the Southern Hemisphere occurred during the late Devonian, while the supercontinent **Gondwana** was located over the South Pole, and intensified during the early Carboniferous. At the same time—while the Southwest was still submerged—the oceans between Gondwana and North America began to close (*Figure 8.5*). In the early Carboniferous, ice capped the South Pole and began to expand northward. Much of the Southwest became an archipelago of warm shallow seaways and **uplifted** islands, with terrestrial swampy forests and shallow sea floors populated by **bivalves**, **brachiopods**, **arthropods**, corals, and fish.

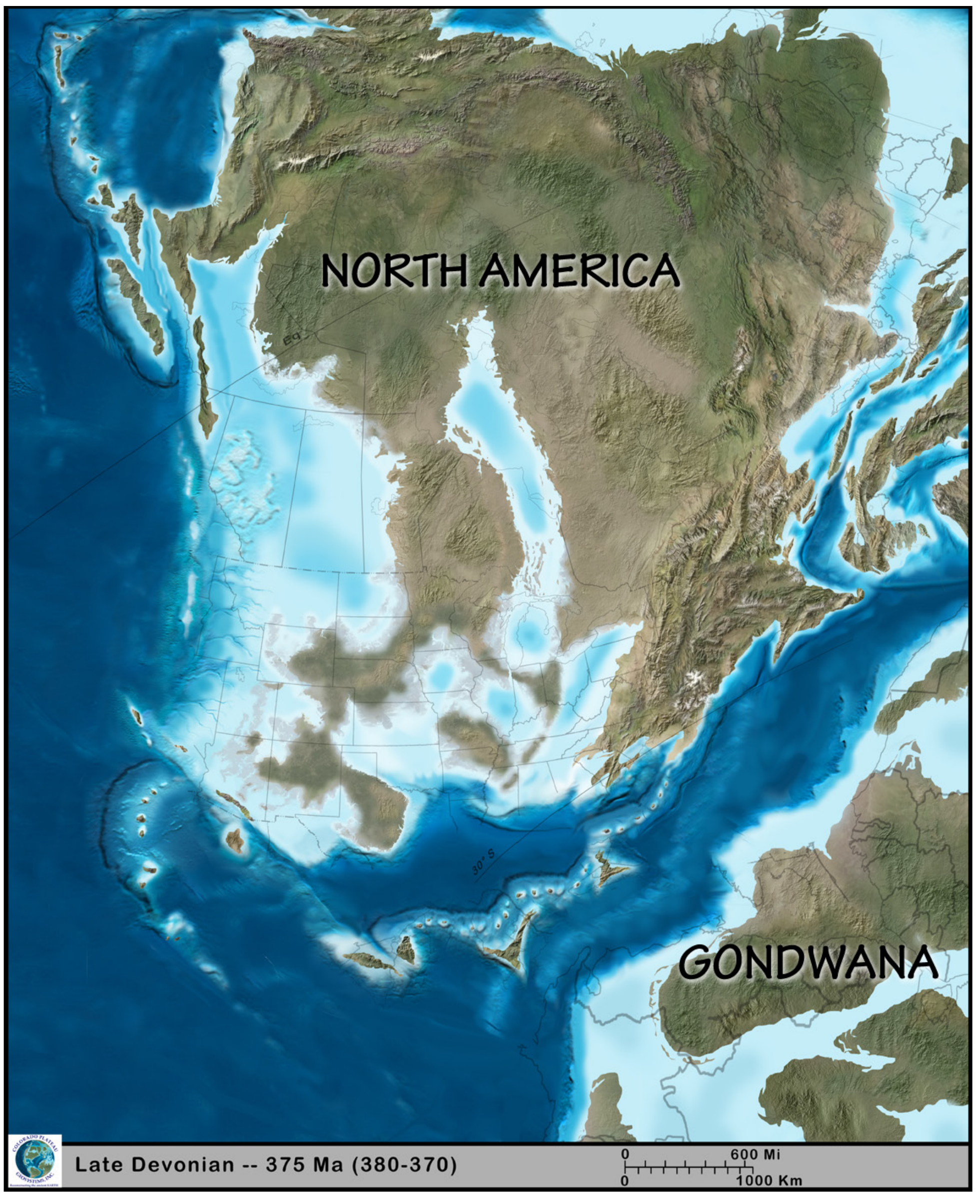


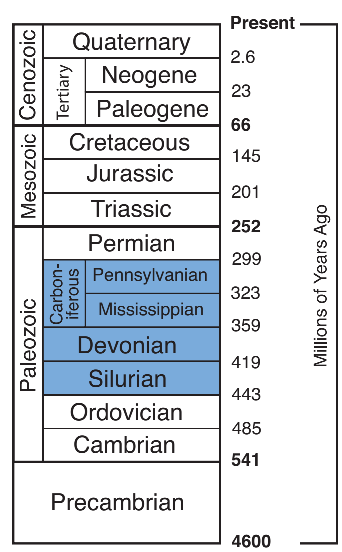
Figure 8.5: By the late Devonian (375 million years ago), the oceans between Gondwana and Euramerica had begun to close.

Gondwana • *the supercontinent of the Southern Hemisphere, composed of Africa, Australia, India, and South America.*

uplift • *upward movement of the crust due to compression, subduction, or mountain building.*

bivalve • *a marine or freshwater invertebrate animal characterized by right and left calcareous shells (valves) joined by a hinge.*

brachiopod • *a marine invertebrate animal characterized by upper and lower calcareous shell valves joined by a hinge, and a crown of tentacles (lophophore) used for feeding and respiration.*



8 Climate

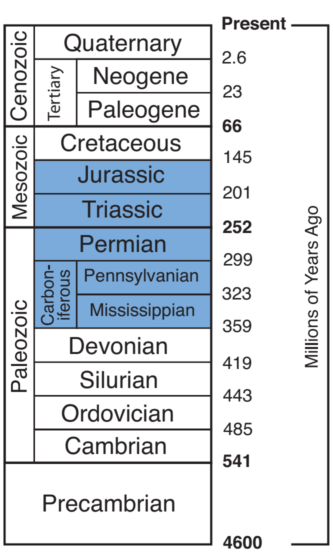
Past

Pangaea • *supercontinent, meaning "all Earth," which formed over 300 million years ago and lasted for almost 150 million years.*

gypsum • *a soft sulfate mineral that is widely mined for its use as fertilizer and as a constituent of plaster.*

synapsid • *a group of tetrapod vertebrates posessing one opening in the skull behind each orbit (eye hole), and a bony arch beneath.*

horsetail • *see sphenopsid: a terrestrial plant belonging to the family Equisetaceae, characterized by hollow, jointed stems with reduced, unbranched leaves at the nodes.*



By the late Carboniferous, North America had collided with Gondwana, leading to the formation of **Pangaea**—a supercontinent composed of nearly all the landmass on Earth. Although the mountain building that occurred during this event was mostly far to the east, the Southwest was influenced by both fluctuating sea levels and a few significant tectonic changes. The climate remained warm, despite large southern ice sheets, but it had grown much drier. In the late Carboniferous, thick salt deposits accumulated in the northwestern Four Corners area as the seas evaporated. Where the land was exposed, deposits of dust (**loess**) accumulated and were blown across much of the Southwest. In southern New Mexico and Arizona, shallow marine deposits, laid down when the ice in Gondwana retreated and sea level rose, alternate with layers of dust blown in when the ice in Gondwana advanced and sea level fell. Loess is often, though not exclusively, associated with dry areas around glaciers. One controversial hypothesis proposes that an area of western Colorado—one of the islands that dotted the early Carboniferous sea—was, in fact, glaciated.

During the **Permian**, shallow marine waters gave way to lowland coastal areas across portions of the Southwest. Extensive Permian deposits throughout the Southwest are home to a host of fossils, including terrestrial amphibians, reptiles, and **synapsids**. The climate was drier than that of the Carboniferous, and mudflats with salt and **gypsum** formed across the Southwestern states. **Sand** dunes started to become widespread. A shift in plant type—from water-loving ferns and **horsetails** to those better adapted to drier conditions—further suggests a change in climate during the Permian. A large, low-latitude desert formed along Pangaea's western margin, generating extensive dune deposits.

See Chapter 2: Rocks to learn more about the cross-bedded Coconino Sandstone and other Permian dune deposits.

By the end of the Permian, the southern ice sheets had disappeared. As the Triassic period began, the Southwest moved north from the equator. The world warmed, and would stay warm through the Mesozoic. The continued growth of Pangaea created an intense monsoonal climate, similar to that of Asia today, that affected large parts of the continent. As Pangaea reached its greatest size during the early Triassic, the monsoon's intensity increased, and the vast dune deserts of the late Permian were replaced by rivers and floodplains. Soils associated with these floodplains testify to the extreme seasonality of rainfall during that time. The monsoon's intensity waned by the early Jurassic, and the rivers and floodplains were replaced by even larger deserts. The Southwest's Triassic-Jurassic dune deposits are some of the most extensive in the world, and the dune field that existed during the Jurassic may be the largest in Earth history. These deposits, including the Navajo Sandstone, are responsible for spectacular scenery in the national parks and recreation areas of northernmost Arizona and southern Utah. Despite the area's arid climate, the dunes were surprisingly full of life, particularly in southeastern Utah. Here, oases with large trees, large colonies of burrowing animals, and reptile **trackways** punctuated the otherwise dry and sandy landscape. These oases were fed by groundwater that originated in the higher country of what is now western Colorado. Later in the Jurassic, the climate became more moderate; dune fields were replaced by rivers and floodplains populated by a rich **dinosaur** fauna (exemplified by the Morrison Formation) and large trees along rivers, streams, and grasslands.

Pangaea began to break up during the Jurassic, **rifting** apart into continents that would drift toward their modern-day positions (*Figure 8.6*). The supercontinent was split by spreading along the mid-Atlantic ridge, initiating the formation of the Atlantic Ocean. As a result of displacement due to continental rifting and sea-floor spreading, sea level throughout the **Cretaceous** was much higher than it is today. Global temperatures during the Cretaceous were very warm, as much as 10°C (18°F) above those at present. There was likely little or no glacial ice anywhere on Earth, and temperatures were highest in lower latitudes. Shallow seaways spread over many of the continents, including South America, Africa, Eurasia, and North America. In the middle Cretaceous, oceans covered most of the Southwest, with the exception of parts of Arizona and New Mexico. By the start of the late Cretaceous, this **inland sea**, called the Western Interior Seaway, divided North America in two (*Figure 8.7*); the water was rich with **mosasaurs**, giant clams, and other marine life. In the late Cretaceous, however, sea level dropped and the western Southwest became a broad coastal plain that hosted lush forests, abundant dinosaurs, and large swamps. By the end of the Cretaceous, uplift to the west was great enough that the resulting hills shed large amounts of sand and **gravel** in an easterly direction, pushing the shoreline eastward until sediment (combined with a worldwide drop in sea level) filled the area formerly occupied by the Western Interior Seaway. As the continents moved closer to their modern positions, the Southwest experienced a hot and humid tropical climate. At the close of the Mesozoic, global climate—though warmer than today—was cooler than at the start of the era.

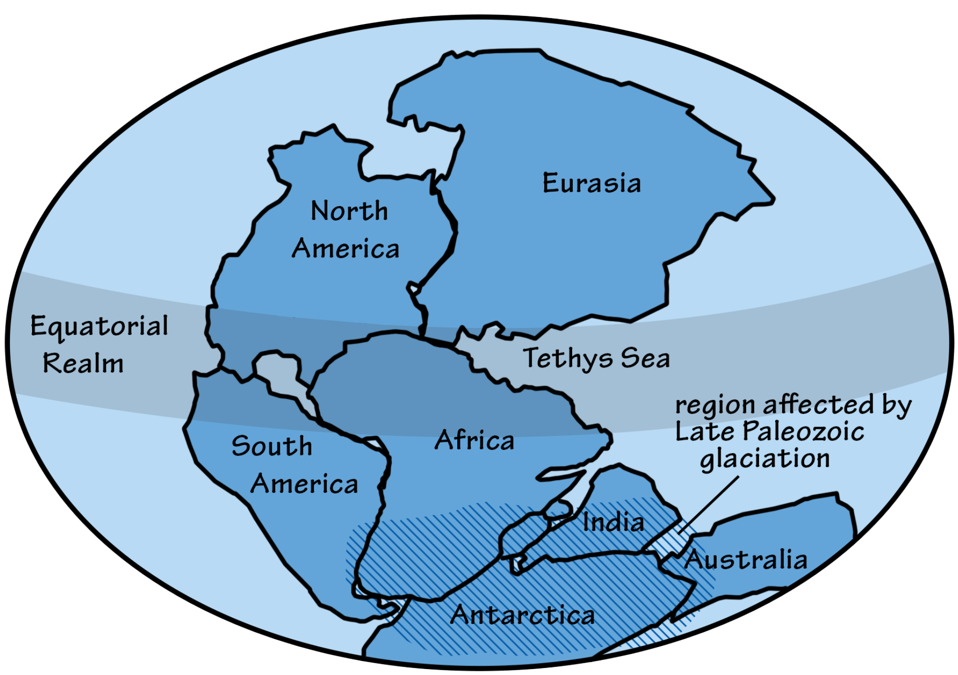


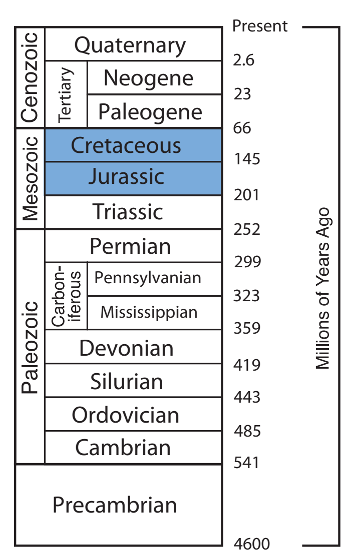
Figure 8.6: The breakup of Pangaea began approximately 220 million years ago.

rift *• a break or crack in the crust that can be caused by tensional stress as a landmass breaks apart into separate plates.*

inland sea *• a shallow sea covering the central area of a continent during periods of high sea level.*

mosasaur *• an extinct, carnivorous, marine vertebrate reptile characterized by a streamlined body for swimming, a powerful fluked tail, and reduced, paddle-like limbs.*

gravel *• unconsolidated, semi-rounded rock fragments larger than 2 millimeters (0.08 inches) and smaller than 75 millimeters (3 inches).*



8 Climate

Past

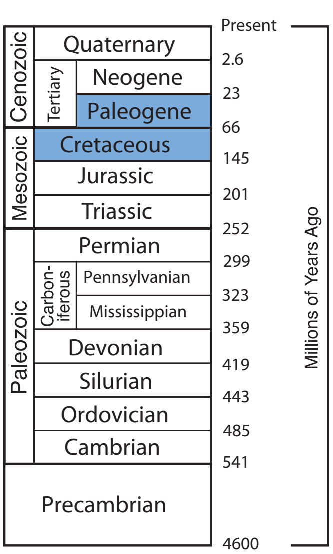
bolide *• an extraterrestrial object of any composition that forms a large crater upon impact with the Earth.*

Eocene *• a geologic time period extending from 56 to 33 million years ago.*

Paleocene *• a geologic time interval spanning from about 66 to 56 million years ago.*

extinction *• the end of species or other taxonomic groups, marked by death of the last living individual.*

Oligocene *• a geologic time interval spanning from about 34 to 23 million years ago.*



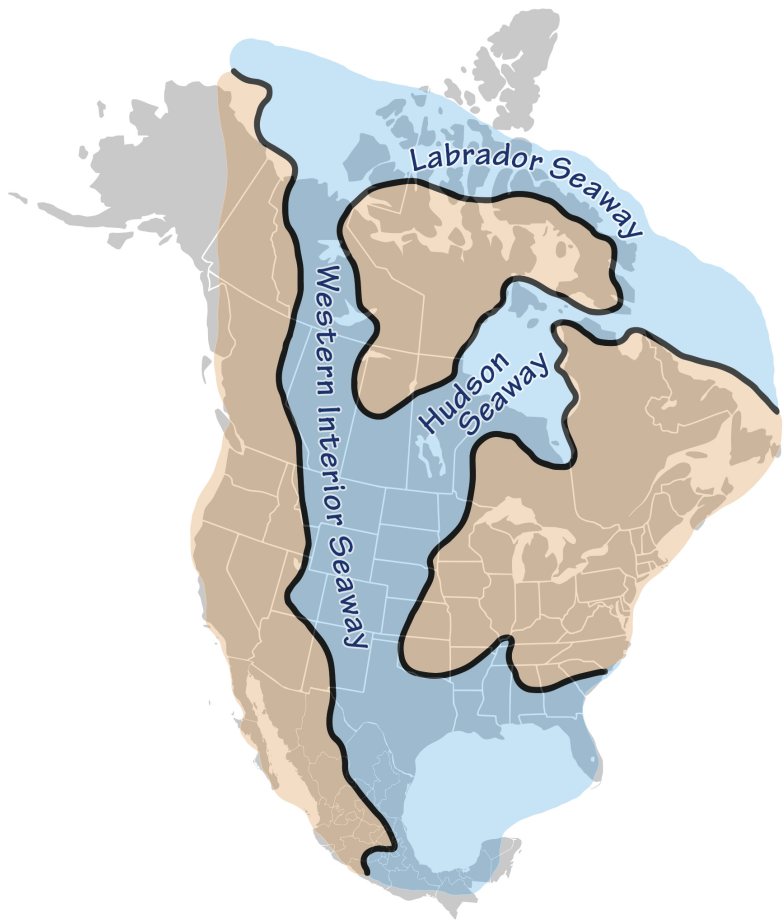


Figure 8.7: The Western Interior Seaway.

At the very end of the Cretaceous, the Gulf Coast experienced an enormous disruption when a large asteroid or **bolide** collided with Earth in what is now the northern Yucatán Peninsula in Mexico. The impact vaporized both water and rock, blocking out sunlight for weeks to years, which led to a collapse of photosynthesis and food webs on land and in the oceans. The event devastated the Southwest, shifting a densely forested landscape to one primarily covered with fast-growing herbs and ferns.

After this event, the climate may have cooled briefly, but it soon rebounded to a warmer state, and the world reached one of its warmest episodes during the **Eocene**. Right at the boundary between the **Paleocene** and Eocene epochs (approximately 56 million years ago), temperatures spiked upward in what geologists call the Paleocene-Eocene Thermal Maximum. During this event, which lasted perhaps only approximately 10,000 years, the atmosphere and ocean warmed by as much as 8°C (14°F) in as little as 4000 years, and deep oceans became acidic, with low levels of dissolved oxygen. The causes of this event remain unclear, but may have involved the sudden release of methane from sediments on the seafloor. The resulting greenhouse effect persisted for 100,000 years. The abrupt climatic change was associated with major migrations, the **extinction** of plants and animals on land, and a mass extinction in the deep sea. The Southwest's climate was warm and wet, with strong volcanic activity, and large mammals roamed the forested landscape. Large lakes covered parts of northern Utah and Colorado.

In the late Eocene, the Earth began to cool, and global temperatures fell sharply at the boundary between the Eocene and **Oligocene** epochs (approximately 35 million years ago), due in part to the separation of South America's southern tip from Antarctica. This allowed for the formation of the Antarctic Circumpolar Current, which insulated Antarctica from warm ocean water coming from lower latitudes and led to the formation of the continent's glaciers. The continents approached their modern configuration, and India began to collide with Asia to form the Himalayas. Global temperatures fell further in the late **Miocene** thanks to the formation of the Himalayas—this event had a significant impact on global climate, as weathering of the newly exposed rock began to serve as a sink to take up atmospheric CO_2. With the reduction of this greenhouse gas, temperatures cooled worldwide, and this cooling has continued more-or-less to the present day. Volcanic activity intensified in the Southwest, and the Basin and Range region began to form, leading to the **topography** that is seen in those areas today (i.e., low valleys alternating with high mountain ranges). While most of the evidence for cooling at the Eocene-Oligocene boundary comes from the deep sea, fossil mammals in the Rocky Mountains show clear evidence of a change from forests to grasslands, which is associated with global cooling.

See Chapter 4: Topography to learn more about the volcanism and tectonics that shaped the Basin and Range.

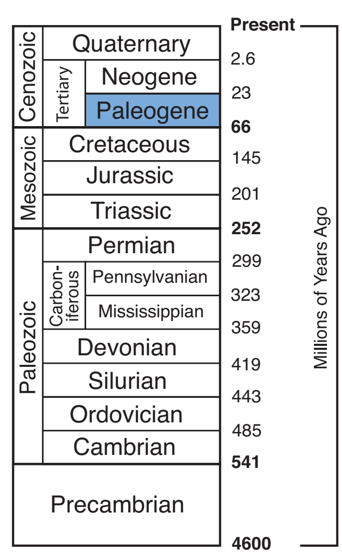
Silicate **and** ***carbonate rocks*** **both weather chemically in reactions that involve CO_2 and water, typically creating** ***clays*****, bicarbonate, and calcium ions. Silica weathering occurs relatively slowly, taking place on a large scale in the weathering and** ***erosion*** **of mountain ranges, and it may have an impact on atmospheric carbon dioxide levels on time scales of tens or hundreds of millions of years. On the other hand, carbonate rocks weather (in this case, dissolve) quickly, relative to silicates. In both cases, the products of weathering often end up in seawater, where they may be used in the** ***calcium carbonate*** **skeletons of marine organisms or taken up during photosynthesis. Skeletal material and organic matter often sink to the sea floor and become buried, effectively removing carbon from the global carbon cycle (and thereby the atmosphere) for many millions of years.**

Miocene *• a geological time unit extending from 23 to 5 million years ago.*

topography *• the landscape of an area, including the presence or absence of hills and the slopes between high and low areas.*

silica *• a chemical compound also known as silicon dioxide (SiO_2).*

carbonate rocks *• rocks formed by accumulation of calcium carbonate, often made of the skeletons of aquatic organisms.*



8 Climate

Past-Present

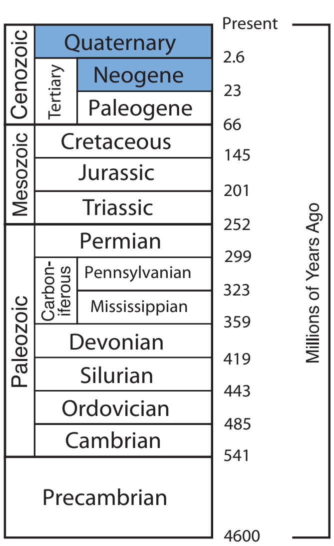
Pliocene • *a geologic time interval extending from roughly 5 to 2.5 million years ago.*

ice cap • *an ice field that lies over the tops of mountains.*

Pleistocene • *a subset of the Quaternary, lasting from 2.5 million to about 11,700 years ago.*

pluvial lake • *a landlocked basin that fills with rainwater or meltwater during times of glaciation.*

heat • *a form of energy transferred from one body to another as a result of a difference in temperature or a change in phase.*



Approximately 3.5 million years ago, glacial ice began to form over the Arctic Ocean and on the northern parts of North America and Eurasia. Surprisingly, a major contributing factor to this event was a geological change that occurred half a world away. The Central American Isthmus, which today makes up most of Panama and Costa Rica, rose out of the ocean at approximately this time, formed by undersea volcanoes. The new dry-land isthmus blocked the warm ocean currents that had been flowing east-to-west from the Atlantic to the Pacific for more than 100 million years, diverting them into the Gulf of Mexico and ultimately into the western Atlantic Gulf Stream. The strengthened Gulf Stream carried more warm, moist air with it into the northern Atlantic, which caused increased snowfall in high latitudes, leading to accelerating cooling. These changes in ocean circulation throughout the Caribbean and Gulf of Mexico also affected nutrient supplies in the coastal ocean, which may have contributed to an increase in the extinction of marine animals (including everything from mollusks and corals to whales and dugongs) during the late **Pliocene**.

Eventually, a sheet of sea ice formed over the Arctic, and ice sheets spread over northern Asia, Europe, and North America, signaling the start of the most recent ice age. Since a mere 800,000 years ago, a type of equilibrium has been reached between warming and cooling, with the **ice caps** growing and retreating primarily due to the influence of astronomical forces (i.e., the combined gravitational effects of the Earth, Sun, moon, and planets). The large ice sheets in the Northern Hemisphere did not extend into the Southwest, even at their largest. However, large glaciers were found at higher elevations, and temperatures were cool. Fossil mammals adapted to colder temperatures are found in the **Pleistocene** of Colorado. In southern New Mexico, Pleistocene fossil mammals are found that now live at higher elevations in the mountains of northern New Mexico, indicating cooler temperatures and more available moisture in the area during the late Pleistocene. Large lakes formed in low areas, and the Southwest's most striking ice age feature was Lake Bonneville—a massive **pluvial lake** that covered much of Utah (*Figure 8.8*). Its remnant exists today as the Great Salt Lake. The last glacial advance of the modern ice age peaked some 18,000 years ago, and today nearly all the glaciers in the Southwest are gone, while the climate is now in an arid state.

See Chapter 1: Geologic History to learn more about the formation of glacial lakes during the last ice age.

Present Climate of the Southwest

The location of the Southwest and the topographical extremes across this area strongly influence its weather. The Southwest experiences nearly every variety of extreme weather; **heat** and cold waves, droughts, floods, blizzards, and even **tornados** are all considerations for residents of the Southwestern states.

See Chapter 9: Earth Hazards for more information on extreme weather in the Southwest.

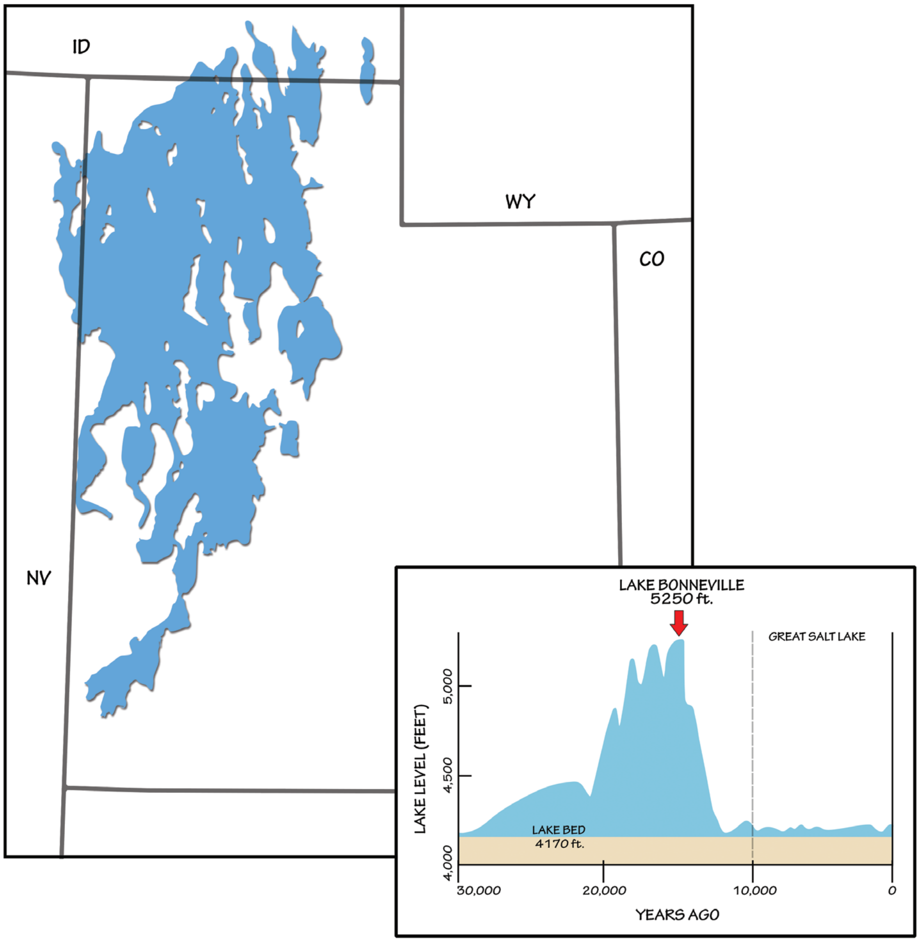


Figure 8.8: Lake Bonneville's maximal extent during the Pleistocene. Inset: Graph of the lake's changing level.

Present

tornado • *a vertical funnel-shaped storm with a visible horizontal rotation.*

Although much of the Southwest falls within the category of an arid zone, using a single label to describe the Southwest's climate would belie its diversity. The main features that influence the area's climate are latitude, regional topography, and a low atmospheric moisture content that leads to quick evaporation. For example, parts of the Colorado Rockies experience cool annual temperatures and over 8 meters (25 feet) of snowfall every year, while the dry deserts in southwestern Arizona receive only about 8 centimeters (3 inches) of precipitation a year and can experience as much as a 15ºC (60ºF) degree temperature difference between night and day.

Average temperatures found in the Southwest tend to decrease northward, which is largely the influence of latitude and elevation. Lower latitudes receive more heat from the sun over the course of a year: for each degree increase in latitude, there is approximately a 1ºC (2°F) decrease in temperature. Higher elevations (such as those found in the Rockies and on the Colorado Plateau) are also cooler, with approximately a 1.5ºC (3°F) decrease in mean annual temperature for each 300-meter (1000-foot) increase in elevation.

8 Climate

Present

The warmest temperatures in the Southwest are found in Arizona and New Mexico, while the coolest are found in Utah and Colorado (*Figure 8.9*). The Southwest's overall average high temperature of 19.2°C (66.6°F) and average low of 2.8°C (37.0°F) are indicative of a varied climate, one much less uniform than that found in many other parts of the United States. By comparison, the average high and low temperatures for the entire United States are 17°C (63°F) and 5°C (41°F), respectively.

Another factor besides latitude and elevation that influences temperature in the Southwest is its arid climate. The lack of moisture in the air allows heat trapped in the earth during daylight hours to rapidly radiate away, leading to cool evenings. Thus, each Southwestern state experiences both extreme highs and lows. In New Mexico, for example, the average difference between the daily high and low temperatures ranges from 14° to 19ºC (25° to 35°F). Record high temperatures for the Southwest range from 53°C (128°F) in Arizona to 47°C (117ºF) in Utah, while record low temperatures range from −56ºC (−69°F) in Utah to −40ºC (−40ºF) in Arizona.

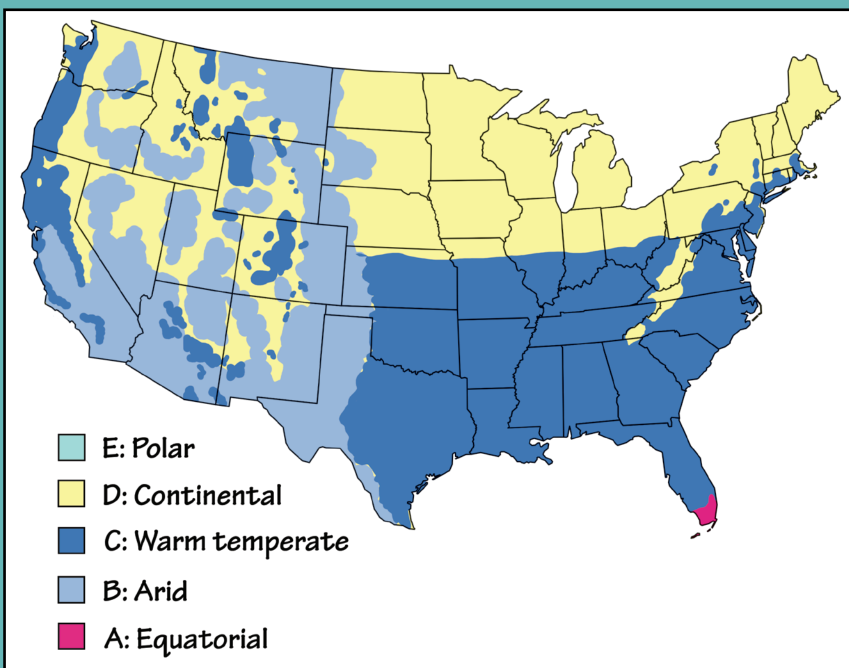
Average Annual Temperatures			
	Overall (ºC [ºF])	**Low (ºC [ºF])**	**High (ºC [ºF])**
Arizona	16.0 (60.8)	7.6 (45.7)	24.5 (76.1)
New Mexico	11.9 (53.2)	3.0 (37.4)	20.3 (68.5)
Utah	9.1 (48.4)	1.5 (34.7)	16.7 (62.1)
Colorado	7.5 (45.5)	−0.9 (30.4)	15.4 (59.7)

The average amount of precipitation for the United States is 85.6 centimeters (33.7 inches). In the Southwest, average precipitation ranges from only 34 centimeters (13.4 inches) in Utah to 39.9 centimeters (15.7 inches) in Colorado, which is indicative of the area's general aridity (*Figure 8.10*). Elevation does, however, play a key role in precipitation received throughout the Southwest. In New Mexico, for example, average annual precipitation ranges from less than 25 centimeters (10 inches) within the Great Plains and Basin and Range regions to more than 50 centimeters (20 inches) at the higher elevations to the northwest. Arizona's highest elevations receive an average of 65 to 76 centimeters (25 to 30 inches), with lower areas in the state's southwestern portion averaging less than 8 centimeters (3 inches). In Utah, areas below 1200 meters (4000 feet) receive less than 25 centimeters (10 inches) per year, while higher elevations in the Wasatch Mountains receive more than 100 centimeters (40 inches).

Across New Mexico, Arizona, and Utah, summer rains originate from moisture brought into the area from the Gulf of Mexico. Warm, moist air from the south occasionally but infrequently moves into Colorado during the summer. During the winter, moisture travels from the west, as storms from the Pacific Ocean move east. Pacific storms lose most of their moisture as they pass over the Rocky Mountains, so much of the Southwest's winter precipitation falls as snow within the area's mountainous regions.

The Köppen Climate Map

Wladimir Köppen developed a commonly used system of climate categorization based on the kinds of vegetation areas sustain. He defined 12 climate types, many of which are familiar: rainforest, monsoon, tropical savanna, humid subtropical, humid continental, oceanic, Mediterranean, steppe, subarctic, tundra, polar ice cap, and desert. Updated by Rudolf Geiger, it has been refined to five groups, each with two to four subgroups.



(See TFG website for full-color version.)

In a broad sense, the Southwest's climate is mostly dry and hot, with much of the region characterized as arid (represented by "B" in the *Köppen system*). Such conditions are common throughout the Great Plains, Colorado Plateau, and Basin and Range. Cold continental conditions (represented by "D") dominate the higher altitudes, especially within the Rocky Mountains. Scattered pockets of drier, Mediterranean temperatures (represented by "C") can also be found.

Present

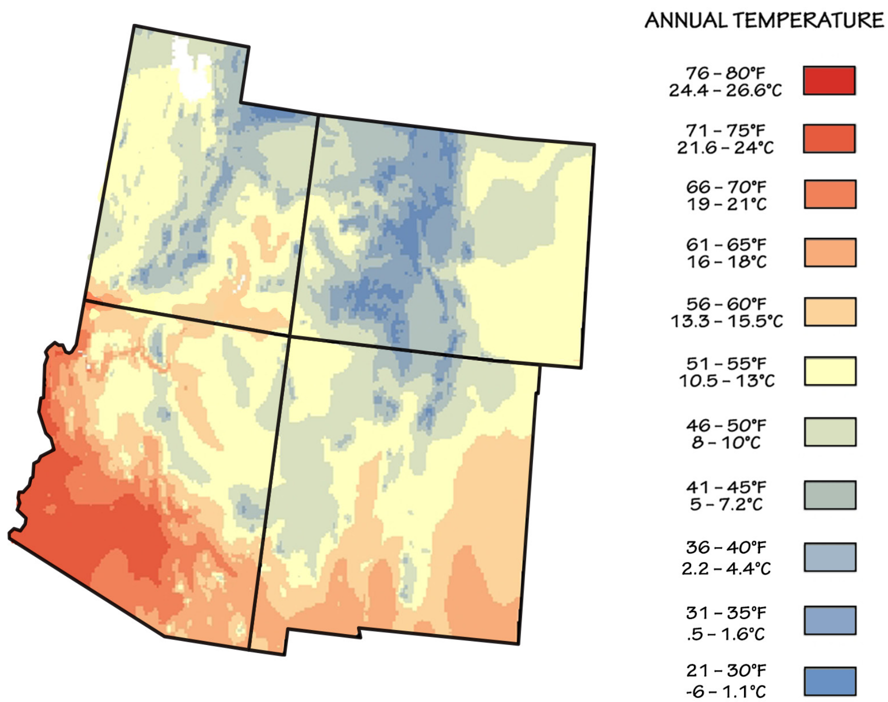


Figure 8.9: Mean annual temperature for the Southwestern states. (See TFG website for full-color version.)

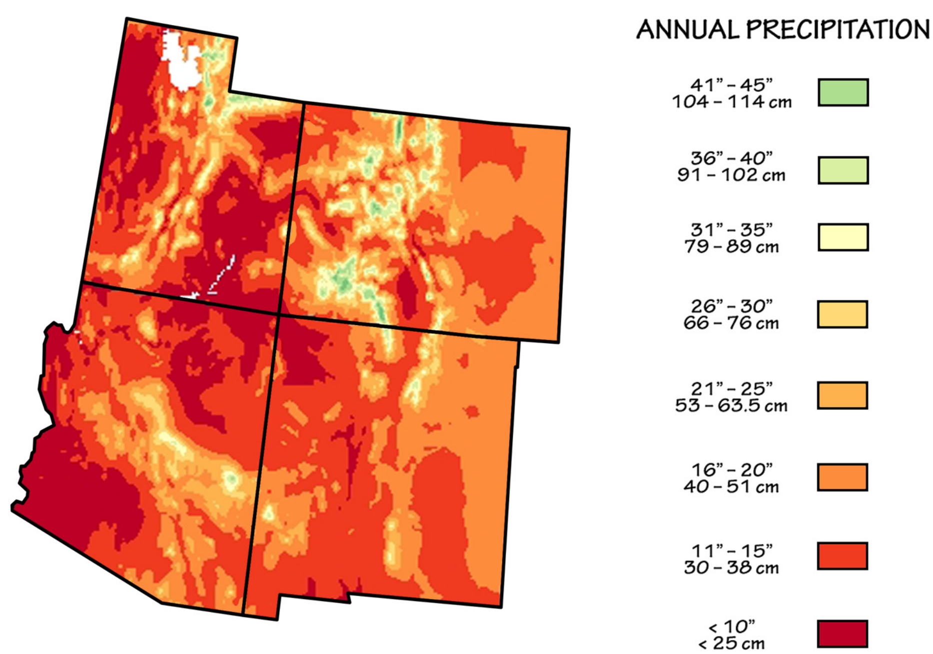


Figure 8.10: Mean annual precipitation for the Southwestern states. (See TFG website for full-color version.)

Present

A strong temperature difference at different heights creates instability—the warmer the air near the surface is relative to the air above it, the more potential energy it has to move up. The Great Plains receive warm, moist air moving north from the Gulf of Mexico, and cold, dry air moving in from the Rocky Mountains and the northern US. Where these air masses meet, vigorous mixing causes thunderstorms. Because warm air can hold more moisture than cool air can, **convective** mixing with cool air forces moisture to condense out of warm air as vapor (clouds) and precipitation. This movement of air in different directions is also the reason for the high incidence of powerful tornados that occur along "Tornado Alley" in the Great Plains (*Figure 8.11*).

See Chapter 9: Earth Hazards to learn more about tornados in the Southwest.

convection • *the rise of buoyant material and the sinking of denser material.*

wind • *the movement of air from areas of high pressure to areas of low pressure.*

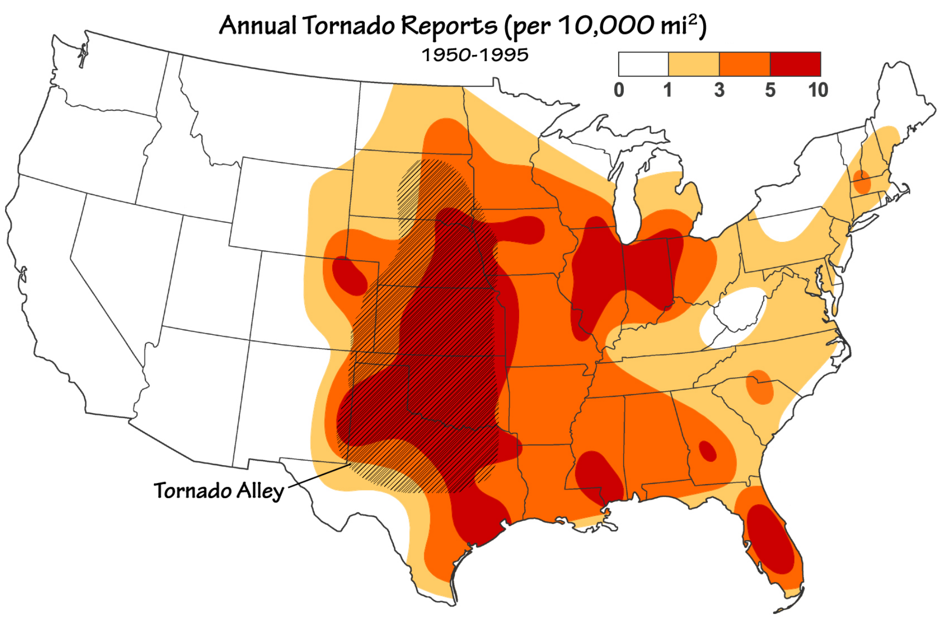


Figure 8.11: Frequency of tornados in the continental US. "Tornado Alley" is an area of the central US known for its violent tornados.(See TFG website for a full-color version.)

Colorado has a generally cool and continental climate, with low humidity. The climate of the eastern plains is fairly uniform, with hot, **windy** summers and prevalent thunderstorms. The state's highest temperatures occur in the northeastern plains, where they can exceed 46ºC (115ºF). Moving westward, Colorado's foothills and mountainous areas experience an overall cooler climate and higher levels of precipitation. Here, the state's varied topography leads to wide changes in climactic conditions that occur across short distances. For example, the difference in annual mean temperature between Pikes Peak (4302 meters [14,114 feet]) and Las Animas (1188 meters [3898 feet]), only 145 kilometers (90 miles) to the southeast, is equivalent to that between Iceland and southern Florida! Precipitation also varies widely—Cumbres in the San Juan Mountains receives nearly 7.6 meters (300 inches) of snowfall annually, while Manassa, less than 50 kilometers (30 miles) away in the San Luis Valley, receives only about 63 centimeters (25 inches) of snow a year.

hurricane • *a rapidly rotating storm system with heavy winds, a low-pressure center, and a spiral arrangement of thunderstorms.*

interglacial • *a period of geologic time between two successive glacial stages.*

anthropogenic • *caused or created by human activity.*

Arizona's climate is influenced by three main topographical areas: the high Colorado Plateau (about 1520–2130 meters [5000–7000 feet] in elevation), the rugged mountains to the west (2740–3660 meters [9000–12,000 feet] high), and the low southwestern mountains with desert valleys (as low as 30 meters [100 feet] above sea level). While the state is generally arid, its high western mountains experience more precipitation each year than the desert southwest and the high northeastern plateau do. The desert also experiences higher temperature extremes, especially between day and night, with a daily change of as much as 15°C (60°F) during the driest parts of the year.

See Chapter 4: Topography for a list of the highest and lowest elevations by state.

In New Mexico, climate is characterized by arid, semiarid, or continental conditions, with light precipitation, low humidity, and abundant sunshine. As in Arizona, the desert experiences a high temperature range daily; the state's mountainous areas, however, have climate characteristics that more closely follow those found in the Colorado Rockies. Summer rains fall almost entirely during brief but intense thunderstorms on the Great Plains, although the occasional **hurricane** in the Gulf of Mexico may push heavier precipitation inland. Winter is the driest season in New Mexico, because precipitation from eastward-travelling Pacific storms is left behind in the western mountains of Arizona and Utah.

Utah's distance from both the Pacific Ocean and the Gulf of Mexico prevents heavy precipitation, and much of the state is typically sunny year-round, with light to moderate winds, although changes in atmospheric pressure during the late fall and winter can lead to an accumulation of haze. Light precipitation travels eastward over the Sierra Nevada and Cascade mountains after dropping heavy snowfall in areas of high elevation. Because high mountains to the west and north act as a barrier to cold Arctic air masses, most areas of Utah rarely experience temperatures below freezing or prolonged periods of extreme cold.

Future Climate of the Southwest

By using techniques that help to reconstruct past climates, and by tracking trends in the present, we can predict how current climates might change. Overall, the world is warming, yet, as we are still in an ice age, eventually the current **interglacial** period should end, allowing glaciers to advance towards the equator again (although likely not for about 100,000 years). However, because the Earth is already getting warmer, the effects of **anthropogenic** warming are

The Earth's orbit, tilt, and wobble alter its position with respect to the Sun, affecting the global climate. These changes in the Earth's movement are cyclical, and the changes in Earth's climate associated with them are known as *Milankovitch cycles.*

amplified through feedback. Some scientists worry that, if not curbed, human activity could actually disrupt the cycle and knock the planet entirely out of the interglacial period, melting all the ice on Earth.

fossil fuels • fuel for human use that is made from the remains of ancient biomass.

Causes of Change

While astronomical and tectonic forces will continue to cause climatic shifts, they act so slowly that they will be overshadowed in the near term by human-induced effects. In 1956, NOAA established the Mauna Loa Observatory (MLO) in Hawai‘i to measure a variety of atmospheric parameters, including carbon dioxide (CO_2) concentration. The CO_2 record extends from 1958 to present, and it shows the influence of both natural and anthropogenic processes (*Figure 8.12*). The zigzag pattern is the result of seasonal photosynthesis in the Northern Hemisphere. In spring and summer, the growth and increased photosynthetic activity of plants draws CO_2 out of the atmosphere. Conversely, it accumulates in the atmosphere during fall and winter when plants are dormant. The overall upward trend is caused by human activity. Industrialization, **fossil fuel** combustion, and deforestation all contribute CO_2 to the atmosphere, adding it at a rate much faster than natural processes can remove it. Analyses of ancient atmosphere samples preserved in glacial ice cores show CO_2 levels to have been 180 parts per million (ppm) at the height of the last ice age and 280 ppm at its end. The amount of CO_2 in the atmosphere has been increasing at a rapid rate since the start of the industrial revolution, and it has accelerated since the end of World War II. In May 2013, measurements at MLO reached 400 ppm CO_2 for the first time.

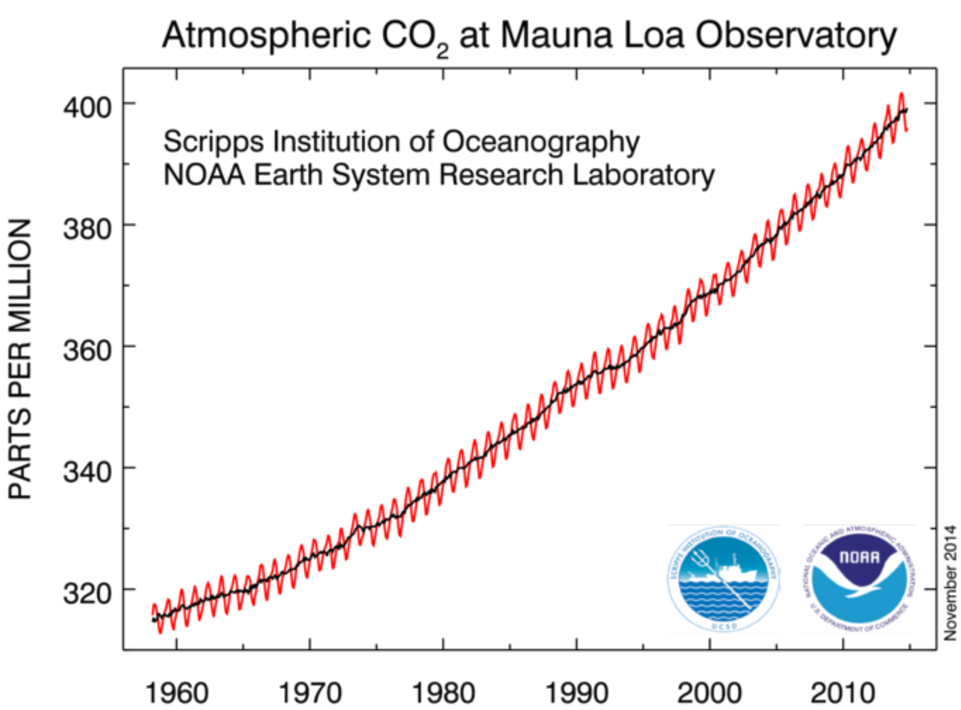


Figure 8.12: Measured concentration of atmospheric carbon dioxide (1958 to present) at MLO.

8 Climate

Future

permafrost *• a layer of soil below the surface that remains frozen all year round. Its thickness can range from tens of centimeters to a few meters.*

aerosol *• tiny solid or liquid particles in the air.*

climate change *• See global warming: the current increase in the average temperature worldwide, caused by the buildup of greenhouse gases in the atmosphere.*

petroleum *• a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface.*

fuel *• a material substance possessing internal potential energy that can be transferred to the surroundings for specific uses.*

natural gas *• a hydrocarbon gas mixture composed primarily of methane (CH4), but also small quantites of hydrocarbons such as ethane and propane.*

While some atmospheric carbon dioxide is necessary to keep Earth warm enough to be a habitable planet, the unprecedentedly rapid input of CO_2 to the atmosphere by human beings is cause for concern. Everything we know about atmospheric physics and chemistry tells us that increased CO_2 leads to a warmer planet. Multiple paleoclimate data sets verify this conclusion, and modern measurements confirm that we are living in an increasingly warmer world. The increasing heat is causing glaciers and sea ice around the globe to melt, and as the ground and ocean they covered is exposed, these darker surfaces absorb and re-radiate increasing amounts of heat.

As **permafrost** in high latitudes melts, carbon in the soil becomes free to enter the atmosphere and, worse, buried organic material can be converted by bacteria into the even more potent greenhouse gas methane. Less directly, higher temperatures lead to more frequent and severe droughts, which, in turn, lead to more wildfires that release carbon and **aerosols** into the atmosphere. Aerosols can have a cooling effect since they reflect away radiation from the sun, but they can also pose a public health hazard.

Water is extremely good at absorbing heat: water vapor is actually the most effective greenhouse gas. Higher temperatures increase evaporation and allow the air to retain more water. While water vapor feedback is the most significant reinforcer of climate warming, water tends to move out of the atmosphere in a matter of weeks—other greenhouse gases, such as carbon dioxide and methane, linger in the atmosphere for years.

The Southwest contributes significantly to **climate change**. The population of any industrialized and particularly wealthy country produces pollution; the majority of these emissions come from the use of **petroleum**. The more than 16 million residents of the Southwest use carbon-rich fossil **fuels** to provide electricity for lighting, cooling, and appliances, to fuel their transportation and industry, and to make the products they use. Burning those fossil fuels releases carbon into the atmosphere, which warms the Earth. Of the Southwestern states, Arizona emits the most greenhouse gases, releasing 94 million metric tons of carbon dioxide per year. Although this pales in comparison to emissions from the nation's highest CO_2 producer—Texas, which releases nearly 656 million metric tons of CO_2 per year—Arizona's greenhouse gas emissions are rising rapidly compared with the nation as a whole. In the last decade, the United States has *decreased* the total amount of energy-related carbon dioxide emissions by almost ten percent, yet Arizona's emissions have *increased* by 9% thanks to a growing population that relies heavily on oil and **natural gas** for energy. Emissions from Colorado and Utah have also increased over the past decade, growing 7% and 2%, respectively.

See Chapter 6: Energy for more information about fossil fuel extraction in the Southwest.

On the other hand, Southwestern states are making changes to reduce human impact on the climate. New Mexico has reduced its CO_2 emissions by more than four metric tons in the last decade. The cities of Aspen and Lafayette, Colorado, as well as the state of New Mexico, were early adopters of the 2030 Challenge, an effort to reduce fossil fuel use in buildings so that both new and renovated buildings would qualify as carbon neutral by the year 2030. Additionally, states are beginning to step up their use and production of **renewable energy**. As of 2015, Arizona ranks 30th in the nation for renewable energy production, much of which it produces from hydroelectricity and **biomass**.

renewable energy • *energy obtained from sources that are virtually inexhaustible (defined in terms of comparison to the lifetime of the Sun) and replenish naturally over small time scales relative to human life spans.*

biomass • *organic material from one or more organisms.*

heat wave • *a period of excessively hot weather that may also accompany high humidity.*

Trends and Predictions

Studies show that the Southwest's climate is changing right now, and that change has accelerated in the latter part of the 20th century. These changes include the following:

- The number of days with temperatures above 35°C (95°F) and nights above 24°C (75°F) has been steadily increasing since 1970, and the warming is projected to continue (*Figures 8.13 and 8.14*).
- The onset of stream flows from melting snow in Colorado has shifted two weeks earlier due to warming spring temperatures. Flows in late summer are correspondingly reduced, leading to extra pressure on the state's water supplies.
- Streamflow totals for the last decade in the Great Basin, Rio Grande, and Colorado River were between 5% and 37% lower than their 20th-century averages.
- Since 1980, tree mortality in forests and woodlands across the Southwest has been higher and more extensive than at any time during the previous 90-year record; this is attributed to higher temperatures, drought, and the eruption of bark beetles that are able to survive through warmer winter weather.
- Increased heat in the Pacific Ocean has altered the weather patterns of Pacific storms, decreasing snowfall in the mountains of western Utah and Arizona.
- In the last decade, the Southwest's frost-free season has increased by approximately 7% compared to the average season length for the 20th century.
- The seasonality and transmission frequency of insect-borne diseases and other infectious diseases prevalent in the Southwest, including plague, valley fever, and Hanta, are influenced by warming trends.

Recent warming within the Southwest has been among the most rapid in the United States, and models predict that the area's climate will continue to warm. The average annual temperature in most of the Southwest is predicted to rise 2.2° to 5.5°C (4° to 10°F) by 2100. Summer **heat waves** will become hotter and longer, while winter cold snaps will occur less often. These increased temperatures lead to a whole host of other effects, including a decrease in snowpack, declines in river flow, drier soils from more evaporation, and the increased likelihood of drought and fires. In winter, rising temperatures have increased the amount of frost-free days—today, most of the Southwest

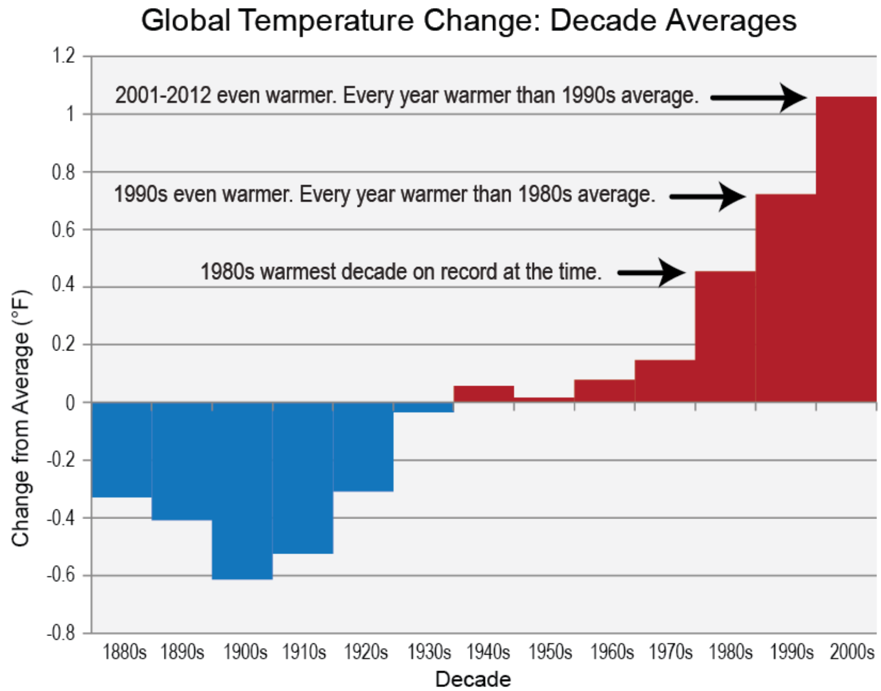


Figure 8.13: Global temperature change since the 1880s. The Earth's average surface temperature has progressively risen over the last five decades.

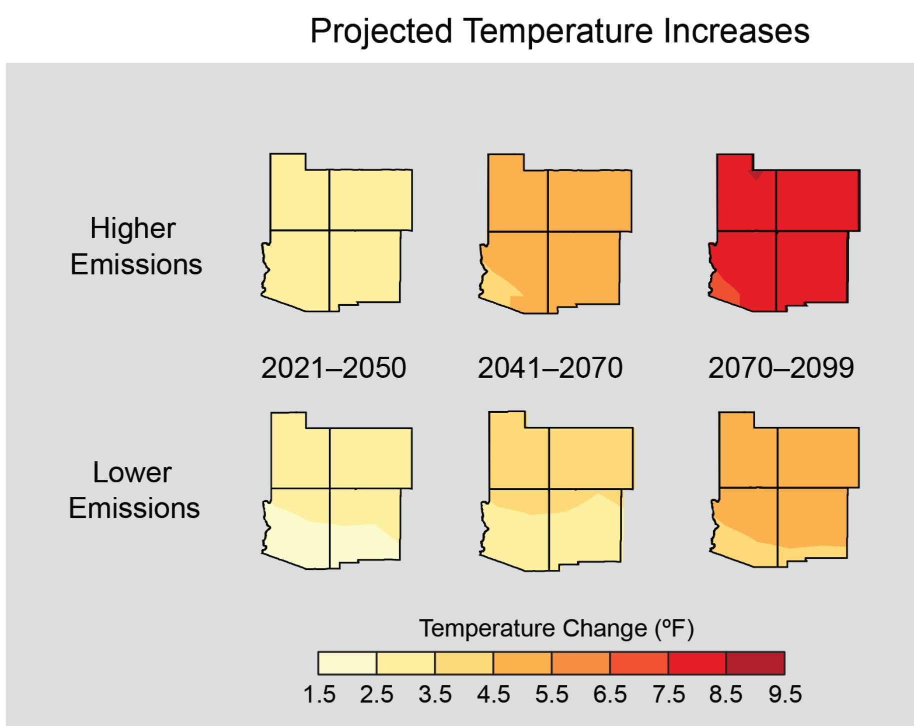


Figure 8.14: Projected temperature increases for the Southwestern states over the next century, as compared to the average for 1971–1999. The "higher emissions" scenario assumes emissions continue to rise, while the "lower emissions" scenario assumes a substantial reduction in emissions. In both cases, temperatures will continue to rise. (See TFG website for a full-color version.)

experiences about 17 fewer freezing days than it did over the last century. By 2070, one can expect up to 38 more days of freeze-free weather each year (*Figure 8.15*). These warmer temperatures and increased precipitation have helped bring on longer growing seasons. While changes in the growing season can have a positive effect on some crops (such as melons and sweet potatoes), altered flowering patterns due to more frost-free days can lead to early bud bursts, damaging **perennial** crops such as nuts and stone fruits.

perennial • *continuous; year-round or occurring on a yearly basis.*

Warmer temperatures also make it easier for insect pests to overwinter and produce more generations. Bark beetles, which normally die in cold weather, have been able to survive through the winter and reproduce, increasing tree mortality. For example, high winter temperatures between 2000 and 2003 correlated to bark beetle outbreaks that devastated pinyon pine throughout the Southwest, leading to nearly 90% mortality at some sites in Colorado and Arizona. As of 2010, bark beetles in Arizona and New Mexico have affected more than twice the forest area burned by wildfires in those states.

Water supply is an important issue in the Southwest, and communities will need to adapt to changes in precipitation, snowmelt, and runoff as the climate changes. Agriculture accounts for more than half of the Southwest's water use, so any major reduction in the availability of water resources will create a serious strain on ecosystems and populations. Drier days and higher temperatures will amplify evaporation, increasing the desertification of already arid areas and affecting natural ecosystems as well as increasing pressure on the water supply for agriculture and cities (*Figure 8.16*). An increased frost-free season length also leads to increased water demands for agriculture and heat stress on plants. Cattle ranches throughout the Southwestern states rely on rain-fed grazing

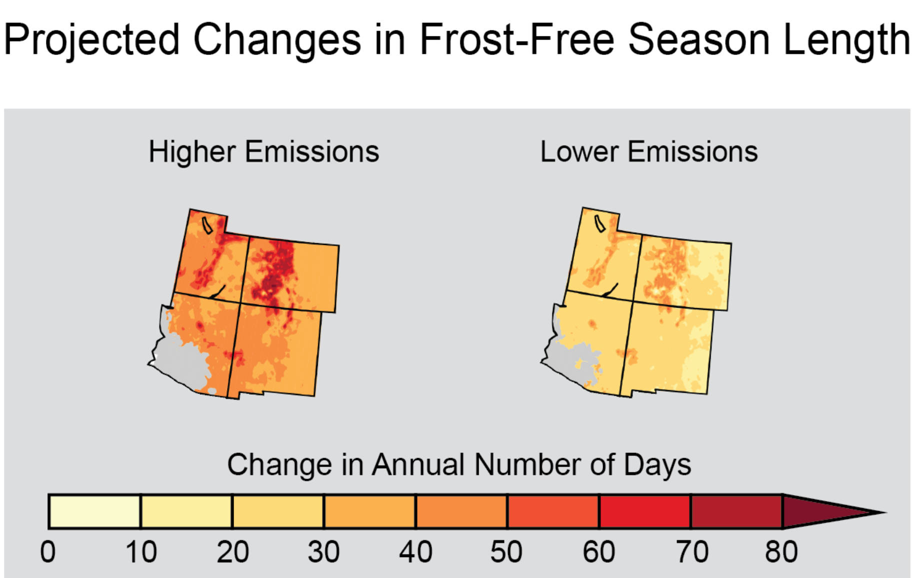


Figure 8.15: Projected frost-free days for the Southwestern states over the next century, as compared to the average for 1971–2000. The "higher emissions" scenario assumes emissions continue to rise, while the "lower emissions" scenario assumes a substantial reduction in emissions. Gray areas are projected to experience more than 10 frost-free years. (See TFG website for a full-color version.)

Future

forage, making them extremely susceptible to climate change and drought. In addition, temperature increases and recent drought lead to earlier spring snowmelt and decreased snow cover on the lower slopes of high mountains, bringing about more rapid runoff and increased flooding. These changes to rain and snow-pack are already stressing water sources and affecting agriculture. Precipitation has become more variable from year to year, and heavy downpours across the US have increased in the last 20 years. Because higher temperatures mean greater evaporation and warmer air can hold more water, precipitation will occur in greater amounts at a time, but less frequently. Although there has so far been little regional change in the Southwest's annual precipitation, the area's average precipitation is expected to decrease in the south and remain stable or increase in the north. Most models predict a decrease in winter and spring precipitation by the middle of the century, and more frequent precipitation extremes during the last half of the century.

See Chapter 9: Earth Hazards for more about the effects of climate change on the environment.

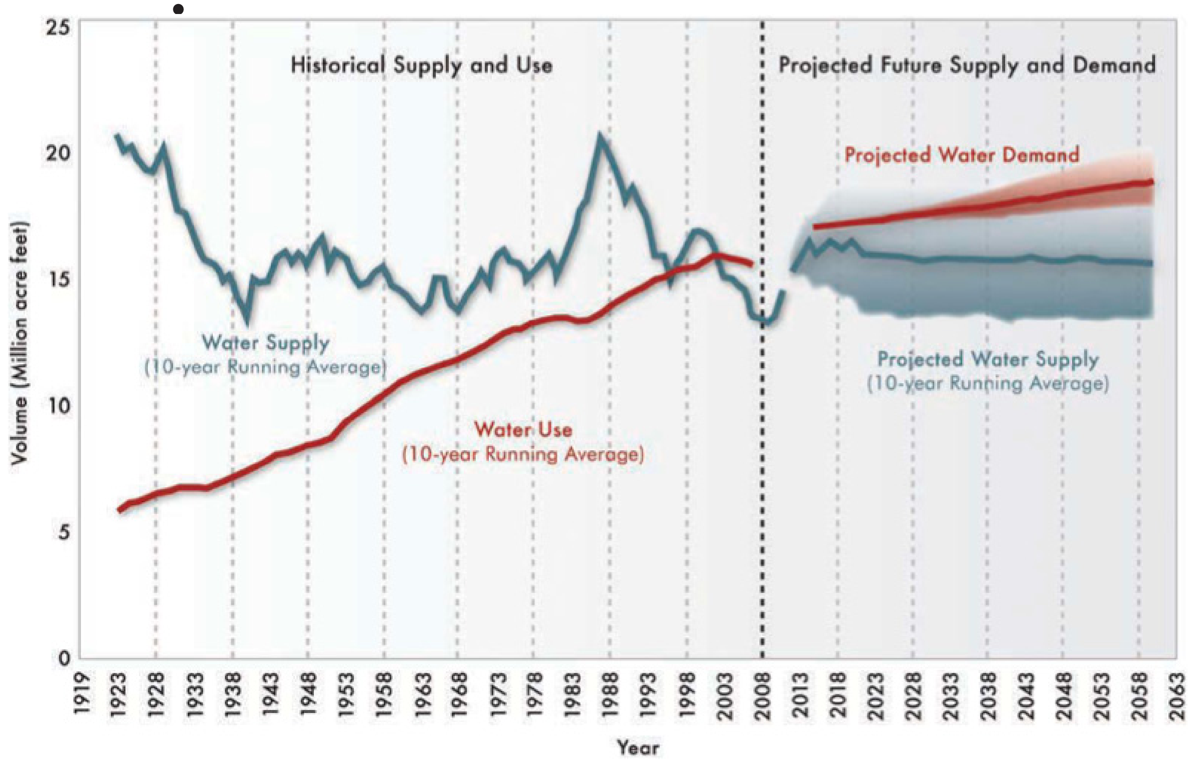


Figure 8.16: Projected 21st-century supply-demand imbalance for the use of water from the Colorado River. The Colorado drains roughly 15% of the continental United States, and is relied upon for municipal and agricultural use by over 35 million people in seven states. (See TFG website for a full-color version.)

The causes of specific weather events such as tornados and severe thunderstorms are incredibly complex, although climate change has enhanced some correlated factors, such as increased wind speed and an unstable atmosphere. Higher atmospheric moisture content has also been correlated with an increased incidence of tornados and winter storms. However, although climate change is predicted to enhance the intensity of severe weather, there is currently no way to calculate what effect climate change will have on the frequency of specific storm events—for example, we might see more powerful tornados, but we do not know if we will see *more* of them.

All over the Southwestern US, residents and communities have begun to adapt to climate change, and to plan for future changes that are expected to come.

Resources

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Climate has Changed Throughout Earth's History, National Park Service, http://nature.nps.gov/geology/nationalfossilday/climate_change_earth_history.cfm.

Climate Literacy & Energy Awareness Network (CLEAN). [A rich collection of resources for educators.] http://www.cleanet.org.

Envisioning Climate Change Using a Global Climate Model, by B. Youngman, M. Chandler, L. Sohl, M. Hafen, T. Ledley, S. Ackerman, and S. Kluge, SERC Earth Exploration Toolkit, http://serc.carleton.edu/eet/envisioningclimatechange/index.html.

Global Climate Change: Vital Signs of the Planet, NASA. [Information about global climate change, including spectacular satellite images.] http://pmm.nasa.gov/education/websites/global-climate-change-vital-signs-planet.

Global Greenhouse Gas Reference Network, Global Monitoring Division, National Oceanographic and Atmospheric Administration Earth System Research Laboratory. [Data and visualizations.] http://www.esrl.noaa.gov/gmd/ccgg/data-products.html.

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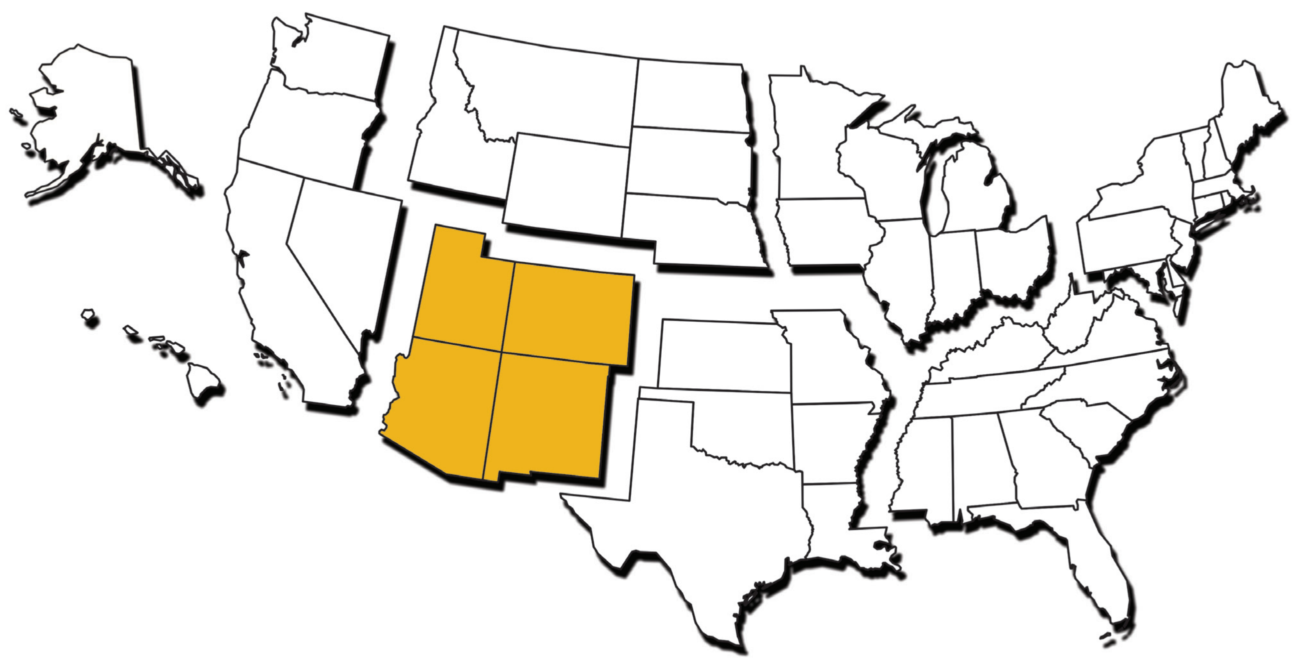

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