Chapter 9: Climate of the Northwest Central 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. Residents of the Northwest Central have a diverse wardrobe, especially in low-lying areas that experience seasonal extremes of hot and cold. The entire area experiences great seasonal variation, although hot summer temperatures are moderated at higher elevations.

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 its long history, parts of the Northwest Central US have been covered in ice, filled with subtropical swamps and forests, and submerged in warm, shallow seas.

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 Northwest Central. Unfortunately, we do not have as clear an understanding of climate

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.*

tree *• any woody perennial plant with a central trunk.*

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

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for the earliest part of Earth 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 exhausted, 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,

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).*

while more buoyant rock floats higher on the **magma** and is pushed around on the slow conveyor belts of mantle-formed rock (*Figure 9.1*). Denser rock forms 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.

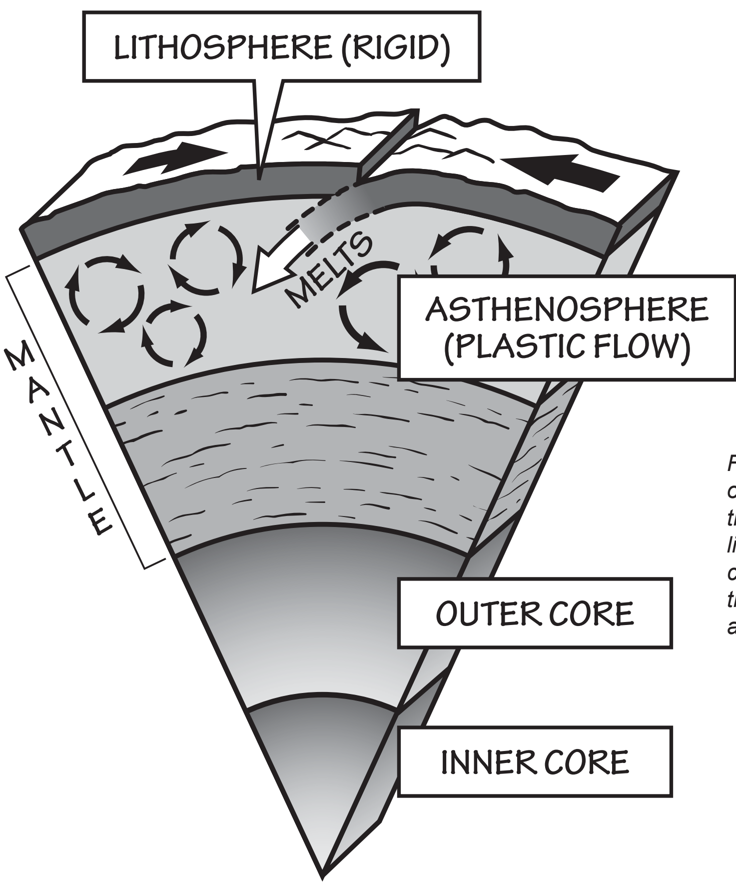

Figure 9.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

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 9.2*). Through the shifting global climate and the movement of the continents, what is now the Northwest Central has at times been submerged beneath a shallow sea, a plain filled with swamps, rivers, and grasslands, and even buried under thick ice.

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

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, rock-forming mineral found in igneous, metamorphic and sedimentary rocks.*

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

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Past

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).

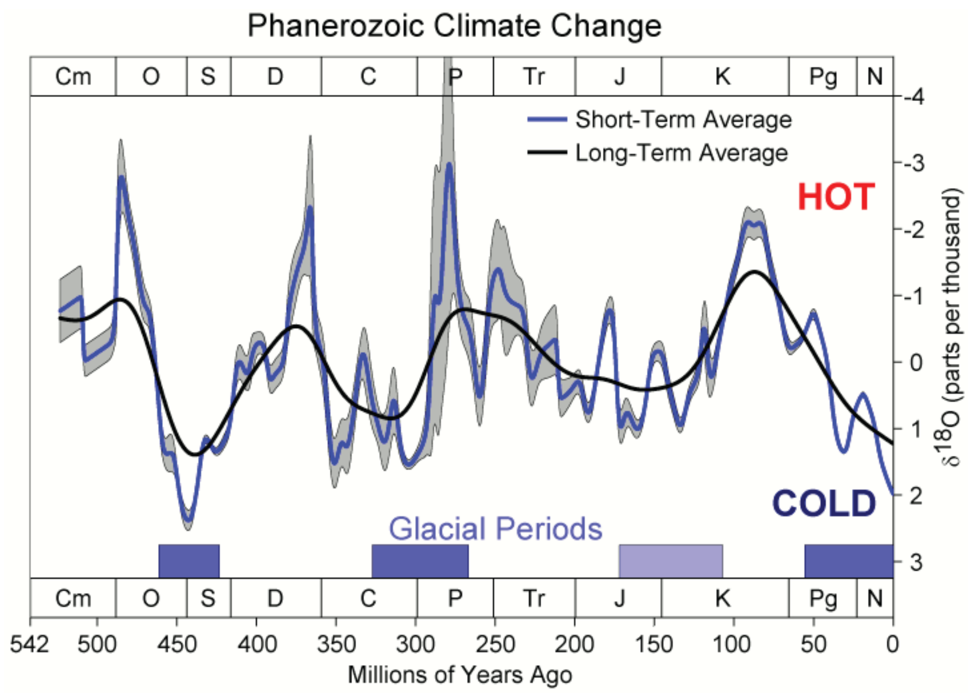

Figure 9.2: Changing global climate throughout the last 542 million years. These data were compiled using the ratios of stable oxygen isotopes found in ice cores and the carbonate skeletons of fossil organisms. (See TFG website for full-color version.)

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 9.3*). 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, which tipped the Earth toward a series of cooling feedbacks, causing ice to spread from pole to pole.

See Chapter 6: Glaciers to learn more about past glaciations.

An ice-covered planet would remain that way because almost all of the sun's energy would be reflected back into space; however, 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

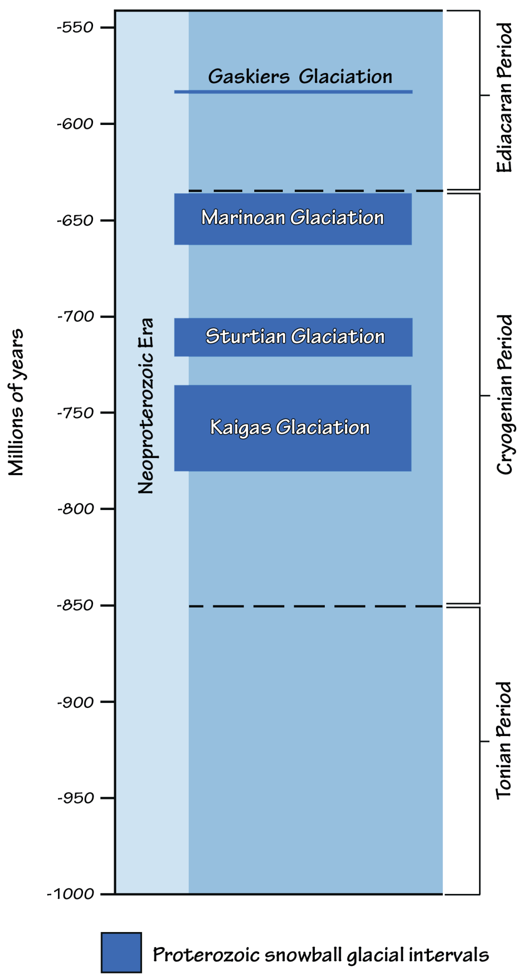

Figure 9.3: Snowball Earth periods during the Proterozoic.

melting started, more of the sun's energy was absorbed by the surface, and the warming feedbacks began. Because the oceans had been covered, nutrients derived from volcanic 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 Northwest Central US, free of ice, drifted around the surface of the Earth. **Stromatolites** found in Glacier National Park in Montana, as well as in Idaho and Wyoming, indicate periods of warm, shallow seas between 1.7 and 1 billion years ago.

A new supercontinent—**Rodinia**—formed, and the part that is now North America was stable, forming what is known as a **craton**, or continental interior relatively free of the folding and **faulting** that characterizes continental margins subjected to mountain building and other plate tectonic processes. About 850 million years ago, during the **Cryogenian**, the Earth entered a 200-million-year **ice age**. The part of Rodinia that would eventually become North America was located near the equator, and there were two more Snowball Earth cycles

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

stromatolite *• regularly banded accumulations of sediment created by the trapping and cementation of sediment grains in bacterial mats.*

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 glaciers.*

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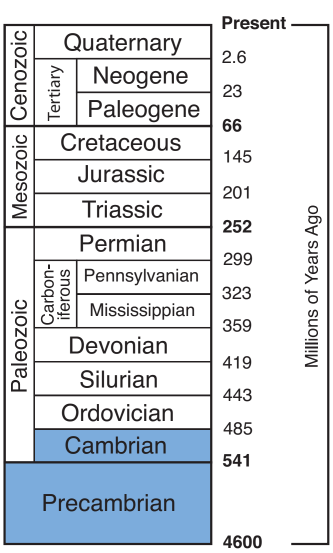
Past

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

__passive margin__ • a tectonically quiet continental edge where crustal collision or rifting is not occurring.

__graptolite__ • an extinct colonial invertebrate animal characterized by individuals housed within a tubular or cup-like structure.

__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.



during this time. Idaho contains deposits from the first of these, called the Sturtian (about 710 million years ago), and the fact that Idaho was at such a low latitude yet still experienced glaciation is strong evidence that the Earth really did freeze over completely. As Rodinia began to break up, another Snowball Earth event occurred during the Marinoan glaciation (about 640 million years ago).

By the late **Precambrian**, 600 to 550 million years ago, the Earth had warmed again, and the North American continent, including most of the modern Northwest Central US, was again near the equator.

Life and Climate

In this Guide we divide the Northwest Central States into five regions, but it is possible to more generally recognize two broad areas of strikingly different geology: the Cordilleran (Idaho, western Montana, and western Wyoming; Regions 3–5) and the Great Plains (North and South Dakota, the rest of Wyoming and Montana, and Nebraska; Regions 1 and 2). The main difference between the two areas is that the Cordilleran area has been subjected to mountain building, while the Plains area has remained tectonically quiet. Throughout most of the **Paleozoic**, the Northwest Central was part of a large **passive margin** that formed when Rodinia broke up, and major changes in deposition there were related to changes in climate and sea level.

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; by about 480 million years ago, what would become the Northwest Central was located just above the equator (*Figure 9.4*). Cambrian fossils reveal that most of the area was covered by warm, shallow seas during this time.

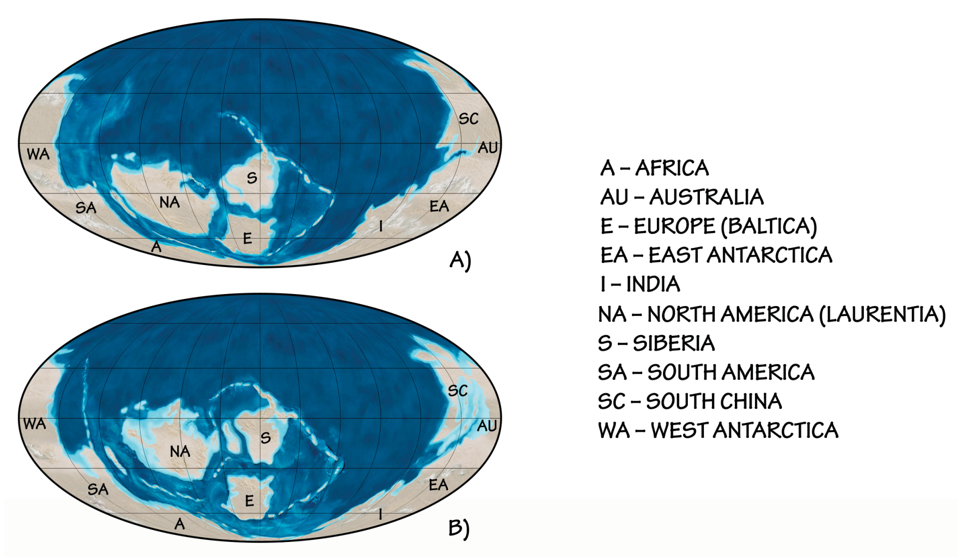


Figure 9.4: The location of the continents during the A) early and B) late Cambrian. Note the position of North America.

Climate 9

Past

The Earth went through another ice age from 460 to 430 million years ago, and although sea level dropped during this event, North America's position near the equator kept its climate relatively warm. The change in sea level meant that the environment of the Plains area fluctuated from shallow marine, to brackish, to freshwater, and back. Farther west, in what is now the northern Rocky Mountains, the environment mostly alternated between shallow and deeper marine. **Ordovician** rocks in Idaho contain abundant fossils of **graptolites**, which are thought to have floated in the open ocean, and thus indicate deeper waters than those implied by bottom-dwelling **brachiopods**, corals, **cephalopods**, and other fossils common in other Paleozoic rocks. One of the characteristics of these warm, shallow sea deposits is that they often alternated between **limestone**, **sandstone**, and mudstone; **reefs** were not common at this time.

See Chapter 3: Fossils to learn more about Paleozoic fossils, including Cambrian trilobites and Ordovician graptolites.

A major interruption in this overall picture occurred during the **Devonian** period, when the huge Bakken oil formation that underlies parts of Montana and North Dakota formed. This oil-rich rock is part of a larger complex of such deposits that covered not just this area but large areas farther east as well. The richness of the organic matter indicates a sea that was highly productive, with such abundant planktonic life that the organic matter from the dead organisms took up all the oxygen in the water, allowing the rest to remain undecayed and preserved in the sediments.

See Chapter 7: Energy to learn about oil-rich deposits throughout the Northwest Central.

During the late Paleozoic, the sea gradually began to withdraw. The Plains area became terrestrial, but the sea still flooded parts of the northern Cordilleran area—this time farther west, in southeastern Idaho—and became exceptionally productive during the **Permian**. This is evidenced by the large deposits of phosphorite—a rock mined for fertilizer in Idaho, Wyoming, and Montana.

See Chapter 5: Mineral Resources for more about phosphate minerals mined in Idaho.

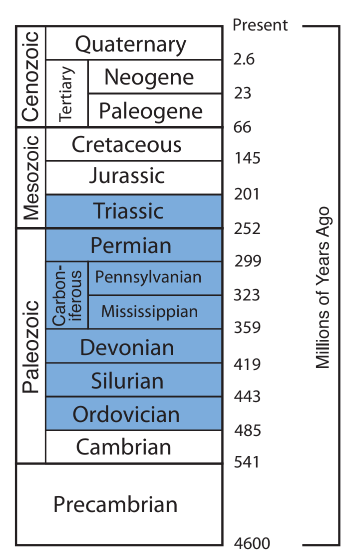
Around 220 million years ago the Northwest Central moved north from the equator. By this time, the sea had withdrawn completely from the area. Sediments suggest that the **Triassic** climate in the Northwest Central was warm. Initially arid, it gradually shifted to a humid climate with abundant, seasonal rainfall. The climate resembled that of modern India, where monsoons soak the land in the summer and completely dry out in the winter. At the very end of the Triassic, climate once again became arid. After reaching its greatest size during the Triassic period, **Pangaea** began to break apart into continents that would drift toward their modern-day positions (*Figure 9.5*).

graptolite *• an extinct colonial invertebrate animal characterized by individuals housed within a tubular or cup-like structure.*

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.*

cephalopod *• a marine invertebrate animal characterized by a prominent head, arms and tentacles with suckers, and jet propulsion.*

Pangaea *• supercontinent, meaning "all Earth," which formed over 250 million years ago and lasted for almost 100 million years.*



9 Climate

Past

microcontinent *• a piece of continental crust, usually rifted away from a larger continent.*

terrane *• a piece of crustal material that has broken off from its parent continent and become attached to another plate.*

subduction *• the process by which one plate moves under another, sinking into the mantle.*

active plate margin *• the boundary between two plates of the Earth's crust that are colliding, pulling apart, or moving past each other.*

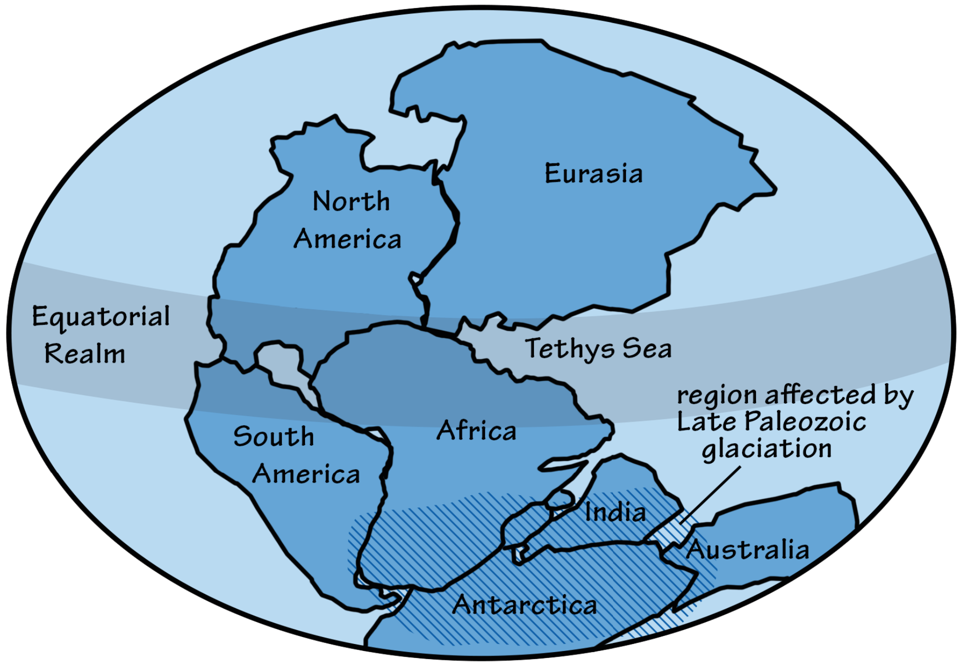


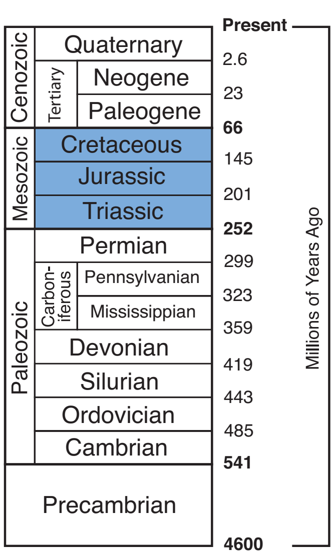
Figure 9.5: The breakup of Pangaea began around 220 million years ago.

Some Triassic rocks now found in the Northwest Central were not, however, part of the continent at that time. Triassic rocks in western Idaho include tropical reefs, and the fossils found in them (such as corals and brachiopods) are not similar to fossils found in the rest of North America. Many parts of the Western US, especially Alaska, originated as **microcontinents** (also called **terranes**) that drifted in during the process of **subduction** at the continent's **active plate margin** and **accreted** to North America as they collided with it. The Triassic reef deposits in Idaho rode in on one such microcontinent.

See Chapter 1: Geologic History to learn about the ways in which subduction and accretion shaped the Northwest Central.

The **Jurassic** and **Cretaceous** climates remained warm, but gradually became wetter, this time without the strong seasonality of the Triassic. The region was ruled by **dinosaurs**, and some of the most famous dinosaur localities in North America, including Como Bluff in Wyoming and the Judith River Formation in Montana, are found in the Northwest Central States. By this time, mountain-building (the **Laramide Orogeny**) was underway. The Black Hills were **uplifted** and sediment was deposited from both west and east. Ancient **metamorphic rocks** of the continental core were uplifted and eventually exposed in the Black Hills and even farther west.

The Earth warmed near the beginning of the Cretaceous, and sea level rose. Throughout the Cretaceous, sea level was an average of 100 meters (330 feet)



higher than it is today, largely as a result of water displacement by continental rifting and rapid sea-floor spreading. Shallow seaways spread over many of the continents, and by the start of the late Cretaceous, North America was divided in two by an **inland sea** known as the Western Interior Seaway (*Figure 9.6*). Areas in the Northwest Central preserve both the eastern and western shorelines of this sea. Cretaceous fossils from modern-day North Dakota show that the seaway supported **sharks**, rays, **mosasaurs** (large marine reptiles), and giant turtles, while crocodiles and dinosaurs were abundant on land. This seaway was also productive, although most of its organic-rich rocks lie just south of the Northwest Central States.

At the close of the Cretaceous, 65 million years ago, global climates (though still much warmer than those of today) were cooler than at the era's start. At the very end of the Cretaceous, the Gulf Coast experienced an enormous disruption when an asteroid or comet collided with Earth in what is now the northern Yucatán

Figure 9.6: The Western Interior Seaway.

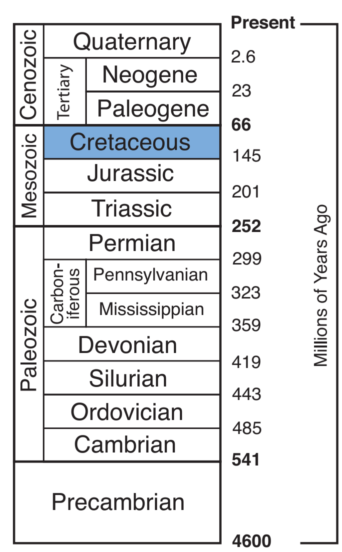
Past

accretion *• the process by which a body of rock increases in size due to the addition of further sedimentary particles or of large chunks of land.*

dinosaur *• a member of a group of terrestrial reptiles with a common ancestor and thus certain anatomical similarities, including long ankle bones and erect limbs.*

Laramide Orogeny *• a period of mountain building that began in the Late Cretaceous, and is responsible for the formation of the Rocky Mountains.*

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



9 Climate

Past

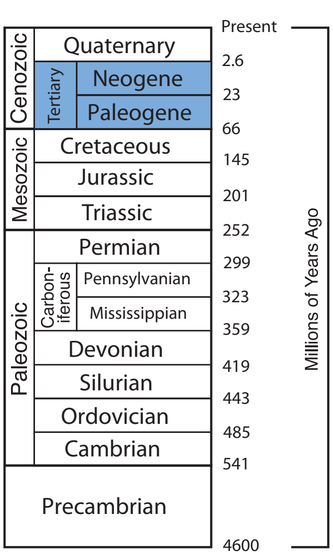
Eocene *• a geologic time period extending from 56 to 33 million years ago.*

soil *• the collection of natural materials that collect on Earth's surface, above the bedrock.*

Cenozoic *• the geologic time period spanning from 66 million years ago to the present.*

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

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



Peninsula in Mexico. Following that event, the climate may have cooled briefly (as suggested, for example, by an abundance of ferns), but it soon rebounded to a warmer state, and continued to warm into the **Eocene**. Around 60 million years ago, much of the Northwest Central US had a milder climate than it does today, and it was even subtropical in some areas. Dinosaurs gave way to mammals, and forests with ferns, palms, and dawn redwoods provided food for browsers. Studies of ancient **soils** show that parts of Montana, Nebraska, and Wyoming went through several periods of warm, wet climate between 35 and 4 million years ago, although overall the climate became drier. The climate was wet enough in the Eocene to support large lakes in Wyoming, although these lakes occasionally dried out. The lakes supported an abundant diversity of fish and other organisms that today are exquisitely preserved as the famous Green River Formation fossils.

See Chapter 3: Fossils to learn more about extraordinary accumulations of perfectly preserved fossils known as lagerstätten.

By the early **Cenozoic**, the continents had approached their modern configuration, and India began to collide with Asia to form the Himalayas. The formation of the Himalayas had a significant impact on global climate, with the newly exposed rock serving as a sink to take up atmospheric CO_2. With the reduction of this greenhouse gas, global temperatures cooled. Antarctica moved south, and by 30 million years ago, temperatures were low enough that glaciers began to grow on its mountains. Grasses evolved during the **Miocene** as climate became drier. Miocene rocks in Nebraska support some of the most amazing sites for fossil mammals known anywhere.

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 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.

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 just 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. During the ice sheet's maximum extent, it reached into Montana, the Dakotas, and Nebraska (*Figure 9.7*). The portions of the Northwest Central that were not covered by ice experienced a variety of cold climates and abundant lakes. These lakes were also related to two very large flooding events, among the largest floods on Earth. The first was the Bonneville megaflood: melting glaciers fed the waters of ancient Lake Bonneville (the remains of which are today the Great Salt Lake), which broke through a dam of loose sediment and rapidly drained northward through southern Idaho, along what is now the Snake River, all the way to northern Idaho. The second was a series of floods that occurred when the ice sheet alternately blocked and retreated from what is now the Clark Fork River in northwestern Montana and northern Idaho. When the river was blocked, an enormous lake built behind the ice dam, and when the ice dam failed,

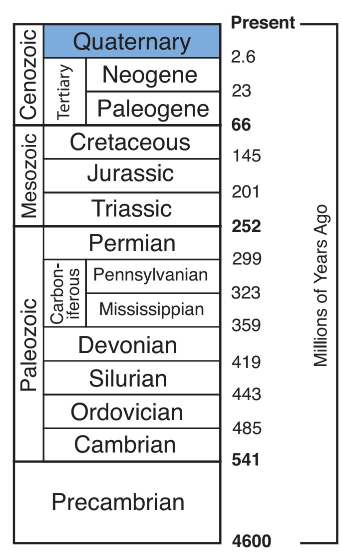
Figure 9.7: Extent of glaciation over North America during the last glacial maximum.

clay *• the common name for a number of very fine-grained, earthy materials that become plastic (flow or change shape) when wet.*

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

calcium carbonate *• a chemical compound with the formula $CaCO_3$, commonly found in rocks in the mineral forms calcite and aragonite, as well as the shells and skeletons of marine organisms.*

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



last glacial maximum • *the most recent time the ice sheets reached their largest size and extended farthest towards the equator, about 26,000 to 19,000 years ago.*

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

Köppen system • *a commonly used system of climate categorization developed by Russian climatologist Wladimir Köppen, based on the kinds of vegetation that areas sustain.*

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

the water was released catastrophically. Although the floods mostly affected central Washington, large ripples from the intense flow are preserved both near Missoula, Montana, and just downstream from where the ice dammed the river in northern Idaho. Between 13,000 and 8500 years ago, fossil evidence shows that spruce and aspen forests grew in areas of North Dakota that are now warmer, drier, and covered with prairie. Idaho became more humid and warmer than it was during the **last glacial maximum**.

Present Climate of the Northwest Central

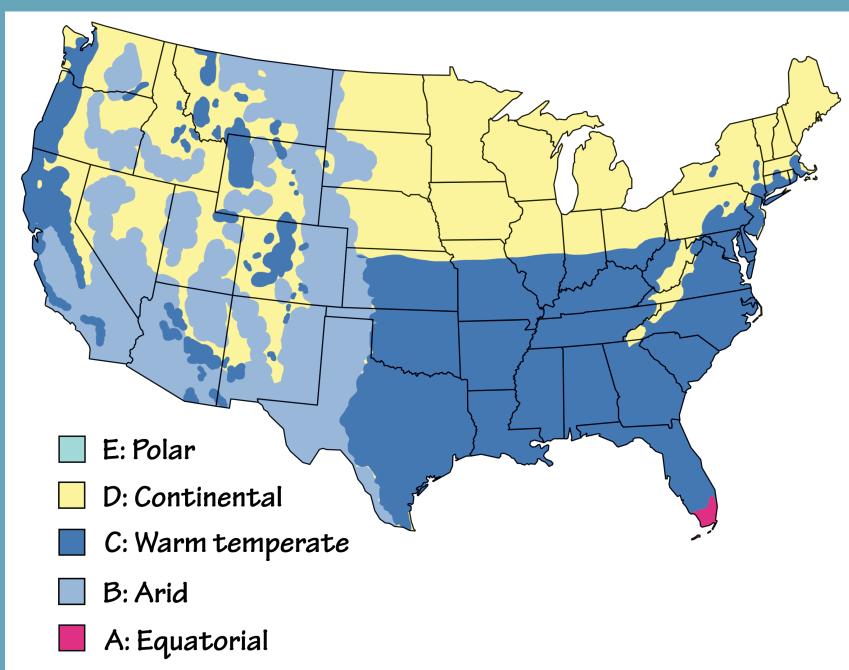
Due to their diverse **topographical** features, the Northwest Central States encompass a broad range of climates, including subarid steppe in the Great Plains, warm temperate highlands in the Cordilleran, and humid continental plains in the eastern Central Lowland. Even individual states can have tremendous diversity—depending on which of the many **Köppen system** maps you refer to, the state of Idaho alone contains as many as eight different climate types. The main drivers of climate in the Northwest Central US are exposure to Arctic air from Canada in the winter, the lack of large bodies of water nearby (except for Idaho, whose climate is influenced by the Pacific Ocean), and the presence of the Rocky Mountain chain in the west. These mountains block moist Pacific Ocean air from the interior of the continent and create a cold, high altitude zone.

Temperatures in the Northwest Central are characterized by seasonal extremes. South Dakota's temperature, for example, varies between an average low of -14°C (6°F) in January and an average high of 86°F (30°C) in July. Record lows and highs are astonishing: -57°C (-70°F) in Montana in 1954 and 49°C (121°F) in North Dakota in 1936. Average temperatures in the Northwest Central tend to decrease northward, which is in part influenced by latitude: lower latitudes receive more **heat** from the sun over the course of a year. The overall warmest temperatures are found in Nebraska, and the coolest are found in North Dakota and parts of Wyoming (*Figure 9.8*). The Northwest Central States' overall average high temperature of 14°C (57°F) and average low of 0.7°C (33°F) are indicative of a generally cool climate. By comparison, the average high and low temperatures for the entire United States are 17ºC (63ºF) and 5ºC (41ºF), respectively.

	Average Annual Temperatures		
	Overall (ºC[ºF])	Low (ºC [ºF])	High (ºC [ºF])
Idaho	6.9 (44.4)	0.8 (33.4)	14.9 (58.8)
Montana	5.9 (42.7)	-0.8 (30.6)	13.3 (55.9)
Nebraska	9.3 (48.8)	2.7 (36.9)	17.0 (62.6)
North Dakota	4.7 (40.4)	-1.2 (29.8)	11.7 (53.1)
South Dakota	7.3 (45.2)	1.3 (34.3)	14.6 (58.3)
Wyoming	5.6 (42.0)	-2.1 (28.2)	13.4 (56.1)

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.)

The Northwest Central US is dry compared with many other parts of the United States, so dry that all the states within it except Nebraska rank within the top 10 driest states based on annual precipitation. Precipitation generally tends to decrease to the west across the Rocky Mountains, with an average annual precipitation of 65–90 centimeters (25–35 inches) in the Central Lowland region of the eastern Dakotas and Nebraska, about 25–50 centimeters (10–20 inches) in the Great Plains, and less than 25 centimeters (10 inches) in parts of Wyoming and Idaho (*Figure 9.9*). By comparison, the average amount of precipitation for the United States is 85.6 centimeters (33.7 inches). The decrease in precipitation is due in large part to rain shadow effects from

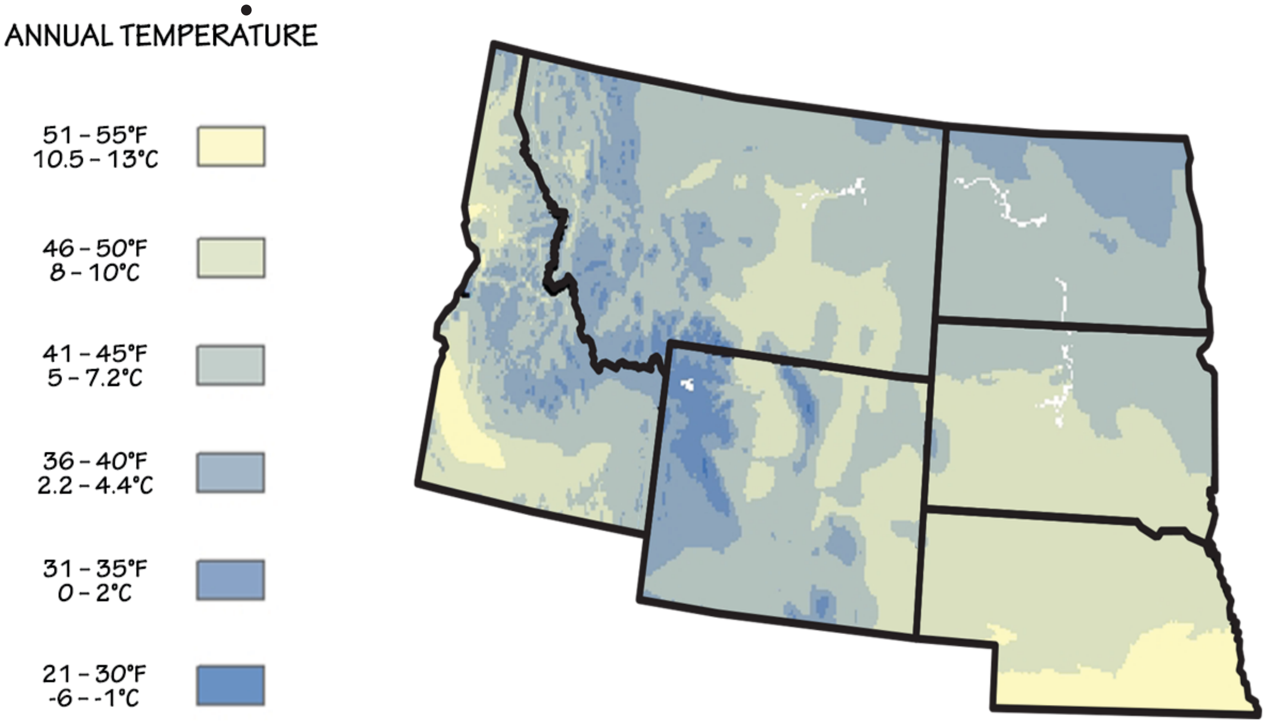


Figure 9.8: Mean annual temperature for the Northwest Central States. (See TFG website for full-color version.)

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

badlands *• a type of eroded topography that forms in semi-arid areas experiencing occasional periods of heavy rainfall.*

mountain ranges located west of as well as within the Northwest Central. Rain shadows occur when moist air moves eastward with the prevailing **winds**, and is pushed upward and cools when it encounters a mountain chain. Water vapor condenses from this cool air and falls as rain or snow on the western side of the mountain. The air that continues to move east over the mountains is now much drier, and as it moves down the eastern side of the mountain range it warms, promoting evaporation (*Figure 9.10*) .The mountainous Continental Divide, which runs through western Montana, creates a rain shadow effect that contributes to the aridity of the plains and **badlands** in the eastern part of the state. Nebraska's semi-arid west and fairly uniform average temperatures are moderated by dry, warm rain shadow winds blowing eastward from the Rocky Mountains.

Exceptions to the westward drying trend are found in the mountainous parts of northwestern Wyoming and Montana, and in northern Idaho, where average annual precipitation is typically 101 to 127 centimeters (40 to 50 inches), demonstrating the impact of moisture carried inland from the Pacific Ocean. Idaho's climate is strongly moderated by the Pacific Ocean, even though the state lies nearly 560 kilometers (350 miles) from the coast. In the winter,

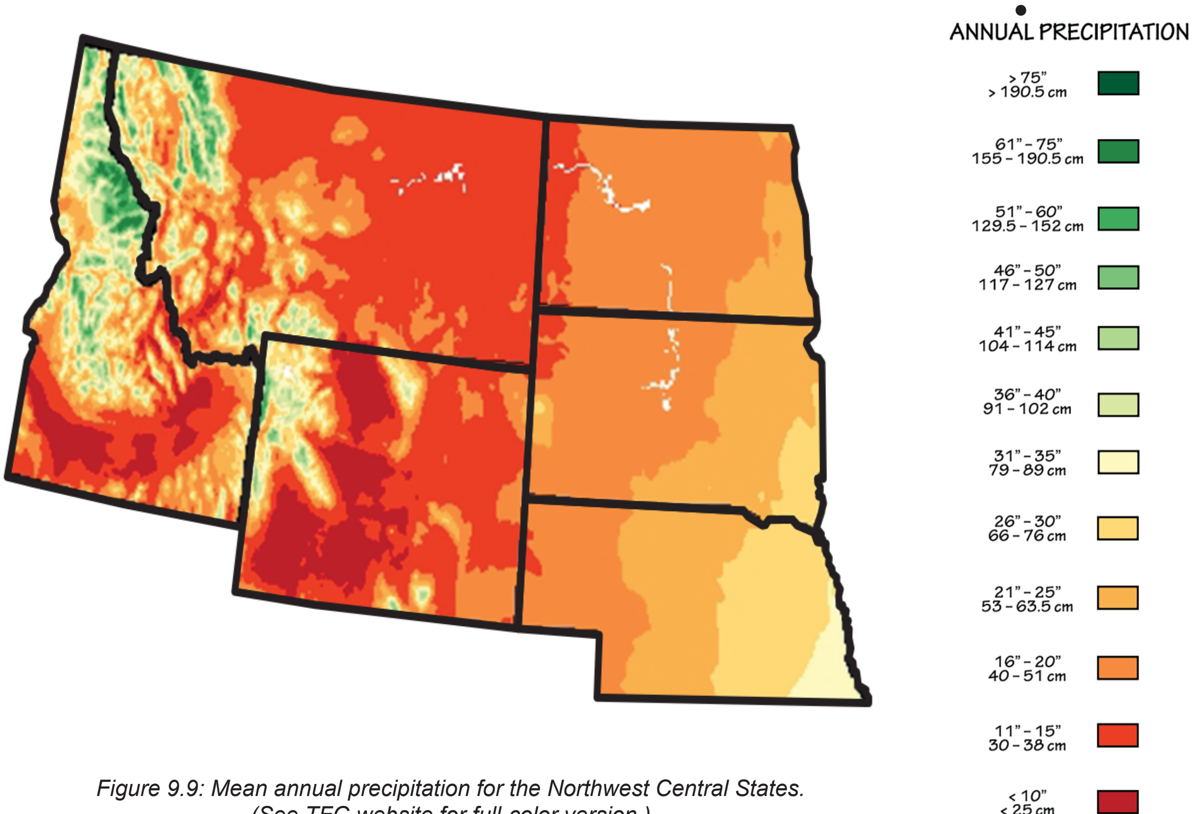


Figure 9.9: Mean annual precipitation for the Northwest Central States. (See TFG website for full-color version.)

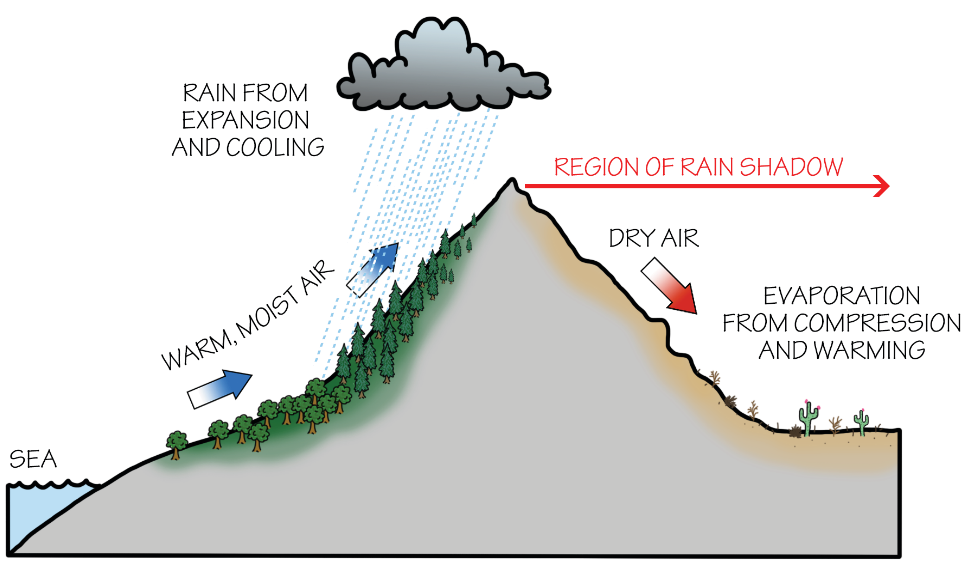


Figure 9.10: The key characteristics of a rain shadow.

Present

jet stream *• a fast-flowing, narrow air current found in the atmosphere.*

erosion *• the transport of weathered materials.*

Figure 9.11: A snow fence near the Grand Tetons in Wyoming. Fences like these are used to force windblown snow to accumulate in a desired place, keeping it off roadways or collecting it for later use as a water supply.

humidity from the ocean creates heavy cloud cover and precipitation that helps to moderate temperature.

Harsh winter storms are a fact of life in the Northwest Central US, carried in by the polar **jet stream**, which typically falls near or over the area, especially in the winter. Blizzards with high winds, large amounts of snowfall, and low visibility are common and are brought on by cold air masses known as the Alberta Low from the north and the Colorado Low from the south. Since the Rocky Mountain region is dry, some residents use fences to capture snow for later use as a water source (*Figure 9.11*). Spring storms are also common, and heavy downpours can lead to flash flooding. Rain coupled with rapid snowmelt in the spring is another common source of flooding in the Rocky Mountain region's river basins.

The Northwest Central US is sparsely populated, with less than seven million people. Weather hazards are a concern for communities and for agriculture. When the area experiences severe drought, as Wyoming did from 1999 to 2004, residents experience costly losses in food and water supply, grazing land for livestock, soil **erosion**, wildfire damage, and air quality. The Red River in North Dakota is highly susceptible to flooding, and since it runs through Fargo and Grand Forks, the populations and infrastructure of those cities are put at risk during floods. In the winter, cold waves brought on by Arctic air masses entering the area

See Chapter 10: Earth Hazards for more information about weather hazards that affect the Northwest Central US.

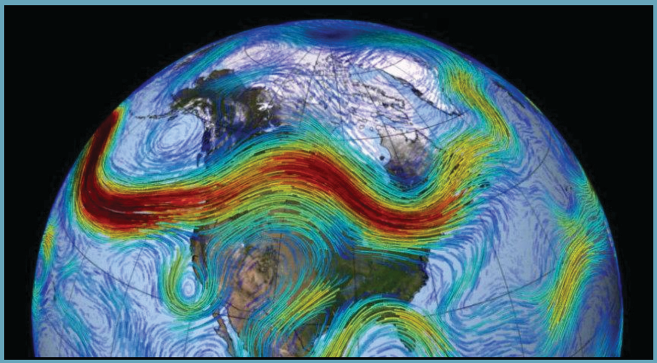
Present

polar vortex • a regularly occurring area of low pressure that circulates in the highest levels of the upper atmosphere.

What is a jet stream?

Jet streams—there are more than one—are narrow bands of fast moving air high above a planet's surface. (Jupiter and Saturn have jet streams too.) The Earth's rotation drives these rivers of air and causes them to blow from west to east. On Earth, they are typically found between 6 and 13 kilometers (4 and 8 miles) above the surface and can move at speeds tens to hundreds of kilometers (miles) per hour. Jet streams separate warm and cold air masses, and thus their movements can greatly influence the weather. Polar jet streams are typically found between 50° and 60° North or South latitude, and subtropical jet streams are typically found around 30° North or South latitude. As the boundaries between hot and cold air are sharpest in the winter months, jet streams are stronger in the winter. In the Northwest Central States, the polar jet stream strongly influences the area's weather.

The *polar vortex* is a pattern of winds around the North Pole, including the polar jet stream. In the winters of 2013–2014 and 2014–2015, the polar vortex shifted southward, bringing unusual weather patterns to much of North America. Weaker polar vortices can occur when weather near the pole is warmer than usual, and a weak polar vortex allows for a wandering jet stream. Some climate scientists believe the unusual winters of recent years are explained by natural variations, while others suggest that they could be driven due to decreases in sea ice and faster increases in arctic temperatures when compared to areas at lower latitudes.



The polar jet stream over North America (shown in red). Warmer colors indicate regions of faster airflow.

(See TFG website for full-color version.)

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

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

anthropogenic *• caused or created by human activity.*

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

can damage livestock and crops. Nebraska, located in a corridor known as Tornado Alley, commonly experiences violent thunderstorms and **tornados** in spring and summer.

Future Climate of the Northwest Central

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, because we are still in an ice age, eventually the current **interglacial** period should end, allowing glaciers to advance toward 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 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.

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 9.12*). 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 be 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.

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.

Future

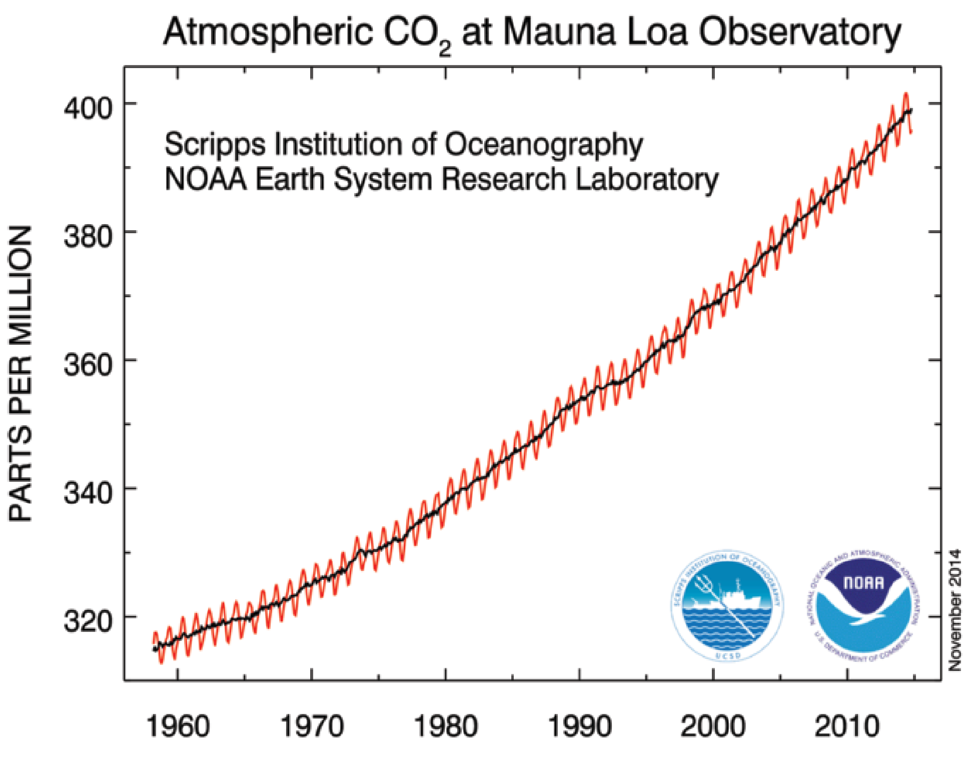


Figure 9.12: Measured concentration of atmospheric carbon dioxide (1958 to present) at MLO.

As **permafrost** in high latitudes melts, carbon in the soil becomes free to enter the atmosphere and, worse, to 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 as 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 Northwest Central US contributes to **climate change**, although its total greenhouse gas emissions are lower than those of other areas of the United States. The population of any industrialized and particularly wealthy country produces pollution; the majority of these emissions come from the use of **petroleum**. The 6.5 million residents of the Northwest Central use electricity, transportation, and products that come from carbon-rich fossil fuels. Burning fossil fuels releases carbon into the atmosphere, which warms the Earth. Of the Northwest Central States, Wyoming emits the most greenhouse gases, releasing 64 million metric tons of carbon dioxide per year. By contrast, the highest greenhouse gas-emitting state in the nation is Texas, which releases

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.*

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.*

nearly 656 million metric tons of CO_2 per year. Idaho is one of the lowest carbon emitters in the nation, producing only 16 million metric tons of CO_2 annually. However, the Northwest Central's low emissions profile is related to its low population. For example, Wyoming has fewer than 600,000 residents; in 2011 it emitted 113 metric tons of CO_2 per capita, the highest in the nation, while Texas, with a population of 26 million, emitted only 23 metric tons per capita.

Although the Northwest Central still has a relatively low carbon footprint, its greenhouse gas emissions have been growing. As recently as 1990, Montana was estimated to be a net carbon sink, with carbon sequestered in its forests and soils. By 2005, it had become a net carbon emitter, and carbon emissions in other Northwest Central States have increased as well. Over the period from 2000 to 2011, Nebraska experienced a 25% increase in the amount of CO_2 it emitted—the greatest absolute increase in the country—due to an increasing amount of fossil fuel-related energy production.

See Chapter 7: Energy to learn about energy production in each of the Northwest Central states.

On the other hand, many Northwest Central States are also making changes to reduce human impact on the climate. Boise, Idaho, Big Sky, Montana, and Jackson, Wyoming are just a few locations that have adopted the 2030 Challenge, an effort by cities to reduce fossil fuel use in buildings so that both new and renovated buildings would qualify as carbon neutral by the year 2030. Additionally, many states are stepping up their use and production of **renewable energy**. Montana ranks ninth in the nation for renewable energy production, most of which it generates from hydroelectricity.

Trends and Predictions

Studies show that climate in the Northwest Central is changing right now, and that change has accelerated in the latter part of the 20th century (*Figure 9.13*). These changes include the following:

- During the 20th century, the average annual temperature of the Northwest Central US as a whole increased by 0.9°C (1.6°F). North Dakota's average temperature increased 1.9°C (3.4°F) during the last 130 years, the fastest increase in the US.
- Soils in Nebraska have become warm enough to plant corn one to three weeks earlier in the 2000s compared to in the 1990s.
- Springtime snowmelts in Wyoming in 1990 were flowing four days earlier than in 1950.
- The Ogalalla Aquifer, which provides fresh water to most of Nebraska, has been depleted by more than 40% in some areas, thanks to years of decreased rainfall.

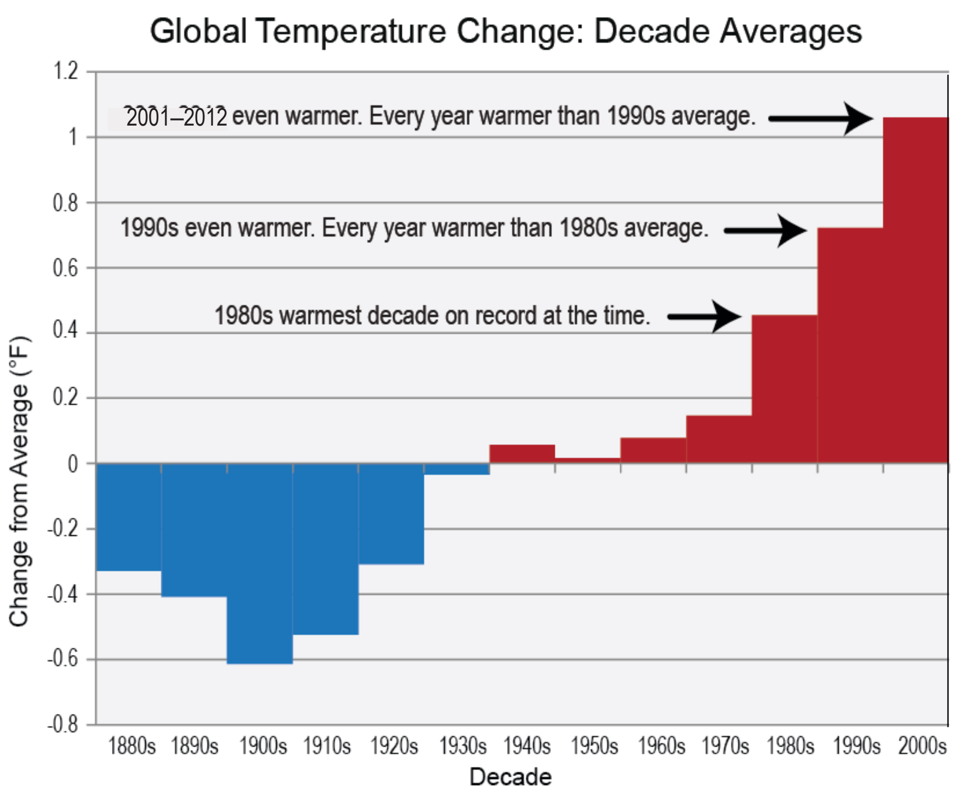


Figure 9.13: Global temperature change since the 1880s. The Earth's average surface temperature has progressively risen over the last five decades.

- The bull trout, an endangered freshwater fish native to northwestern North America, is estimated to have lost 11% of its stream habitat in Idaho's Boise River Basin due to an increase in water temperature.
- In the last century, annual precipitation has increased by up to 20% in South Dakota.
- In 1850, Montana's Glacier National Park contained an estimated 150 glaciers. Today, only 25 glaciers remain. Models predict that all of them will have disappeared by 2030.

Climate models predict that the Northwest Central's climate will continue to warm, and that the average annual temperature in most of the area will rise by 3°C to over 6°C (6°F to over 10°F) by the end of the 21st century. These increased temperatures lead to a whole host of other effects, including drier soils from greater evaporation, and the increased likelihood of drought and fires. In Montana, for example, the annual amount of wildfire-prone land area is predicted to increase by nearly 400% by the end of the century.

9 Climate

Future

Water supply is a critical issue in the Northwest Central US, and communities will need to adapt to changes in precipitation, snowmelt, and runoff as the climate changes. Models predict that much of the area's climate will become wetter, with more precipitation falling in winter and spring. In Idaho, it's likely that increasingly more precipitation will fall as rain rather than snow, and snow in the mountains will melt earlier in the spring. This could strain the water supply in the warm season. Additionally, because higher temperatures mean greater evaporation and warmer air can hold more water, precipitation will occur in greater amounts at a time (*Figure 9.14*). During the cooler spring this will lead to flooding, while in hot summers, droughts will become more frequent. These drier summers and wetter winters and springs could have significant adverse impacts—drier summer days and higher temperatures will amplify evaporation, increasing the risk of desertification and affecting natural ecosystems as well as increasing pressure on the water supply for agriculture and cities.

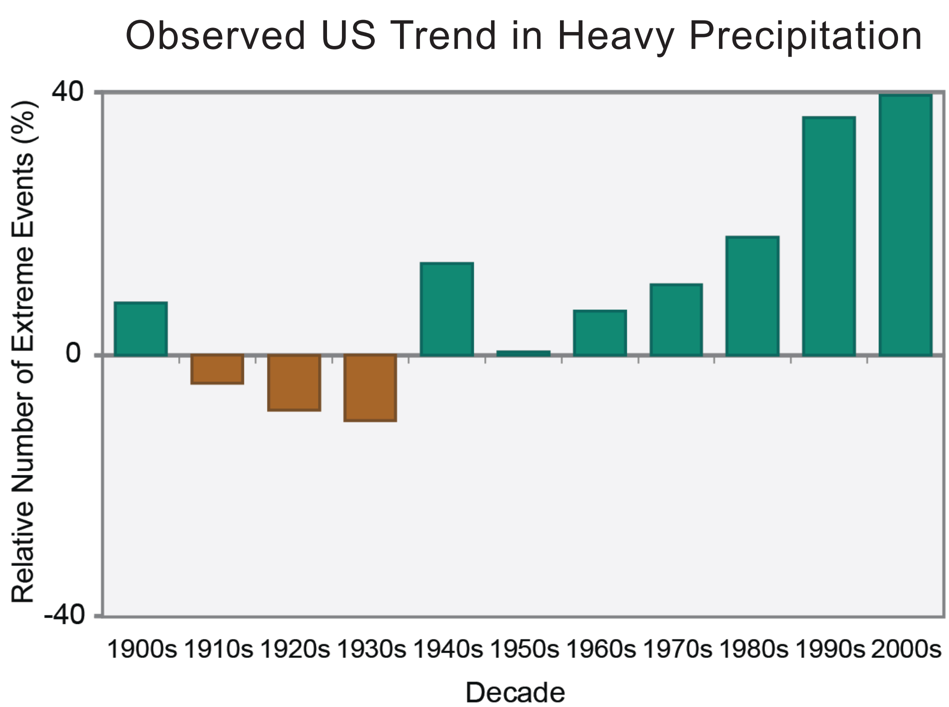


Figure 9.14: Changes in heavy precipitation events from the 1900s to the 2000s. Each event is defined as a two-day precipitation total that is exceeded, on average, only once every five years. The occurrence of such events has become increasingly common.

Agriculture is a huge industry in the Northwest Central US, especially in the Great Plains and Central Lowland. To the advantage of soybean and corn growers in Nebraska, warmer temperatures and increased precipitation have helped bring on longer growing seasons. Warmer temperatures, however, also make it easier for insect pests to overwinter and produce more generations. The European corn borer, a devastating pest found in the central and eastern US, produces more generations in warmer parts of the country (*Figure 9.15*).

Future

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

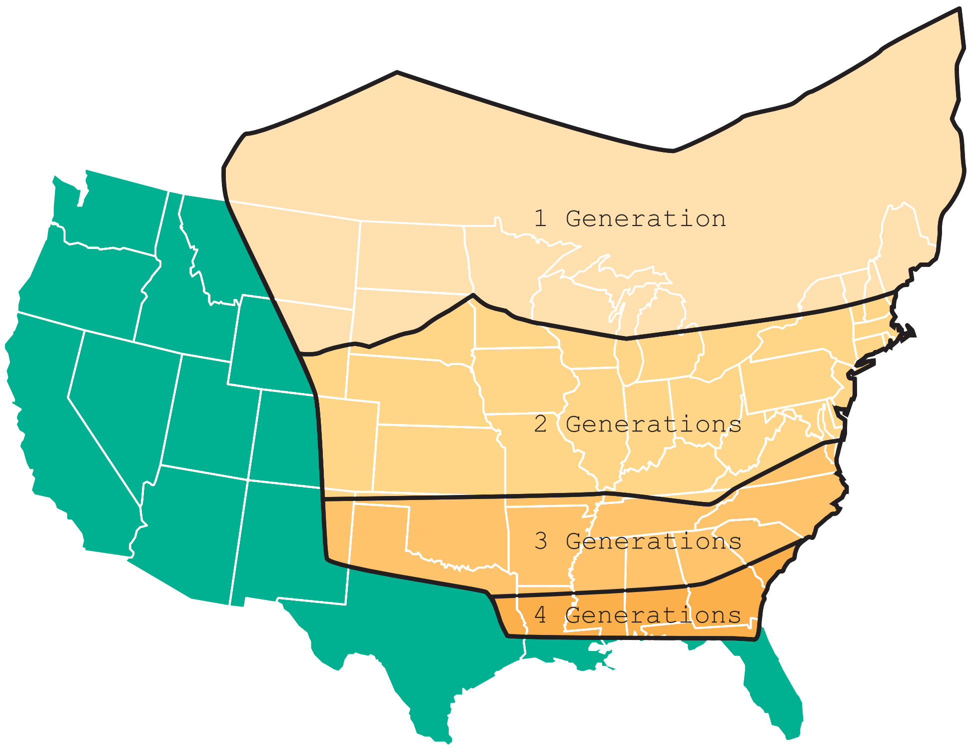


Figure 9.15: The European Corn Borer, an agricultural insect pest, currently produces one to four generations a year depending on its location in the US. As the climate warms farther north, they are expected to produce more generations in the Great Plains and Central Lowland, causing greater crop damage.

As the Great Plains and Central Lowland warm, one can expect three or four generations of these pests annually in regions that previously had only one or two. Another major pest affected by the warming climate is the mountain pine beetle, which has been devastating pine forests throughout the Pacific Northwest and Canada, and is now spreading west into Montana, Wyoming, and the Dakotas. In the last few years, the beetle's numbers have spiraled out of control thanks to warmer temperatures, which extend the breeding season and generate fewer cold-related dieoffs for the insect population. So far, 36 million hectares (88 million acres) of pine forest have been affected, with a 70–90% tree mortality rate (*Figure 9.16*). The death of these trees will have a significant impact on the forests' ability to sequester carbon; researchers have estimated that the dieoffs in Canada alone will have caused the release of 270 million metric tons of CO_2 into the atmosphere by 2020.

The causes of specific weather events such as **hurricanes** 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

Figure 9.16: A swath of dead trees in the Black Hills of South Dakota, destroyed by the mountain pine beetle.

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 Northwest Central US, residents and communities have begun to adapt to climate change, and to plan for future changes that are expected to come.

Resources

General Books and Articles on Climate

Allmon, W. D., T. A. Smrecak, and R. M. Ross, 2010, *Climate Change—Past Present & Future: A Very Short Guide*, Paleontological Research Institution, Ithaca, NY, 200 pp.

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Ruddiman, W. F., 2014, *Earth's Climate: Past and Future, 3rd edition*, W. H. Freeman, New York, 445 pp.

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Climate, National Oceanic and Atmospheric Administration, http://www.noaa.gov/climate.html.

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), http://www.cleanet.org. (A rich collection of resources for educators).

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, National Aeronautics and Space Administration, http://pmm.nasa.gov/education/websites/global-climate-change-vital-signs-planet. (Information about global climate change, including spectacular satellite images.)

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

Global Weather, Jetstream—Online School for Weather, National Weather Service, http://www.srh.noaa.gov/jetstream/global/global_intro.htm.

Intergovernmental Panel on Climate Change, Fifth Assessment Report (AR5), http://www.ipcc.ch/.

JetStream—Online School for Weather, National Weather Service, National Oceanographic and Atmospheric Administration, http://www.srh.noaa.gov/jetstream/index.htm.

National Climate Assessment, http://nca2014.globalchange.gov. (Reports summarizing impacts of climate change.)

National Weather Service, National Oceanographic and Atmospheric Administration, http://www.weather.gov.

NOAA's El Nino Portal, National Oceanographic and Atmospheric Administration, http://www.elnino.noaa.gov/.

Resources

North America During the Last 150,000 Years, compiled by J. Adams, http://www.esd.ornl.gov/projects/qen/nercNORTHAMERICA.html.

Paleomap Project, http://scotese.com/. (Maps and information about Earth's tectonic and climate history.)

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment, National Oceanographic and Atmospheric Administration, http://www.nesdis.noaa.gov/technical_reports/142_Climate_Scenarios.html.

US Map of Köppen-Geiger Climate Classification, http://koeppen-geiger.vu-wien.ac.at/pics/KG_USA.gif.

Weather Base, http://www.weatherbase.com. (Weather and climate data by country, state, and city.)

Weatherunderground Maps, http://www.wunderground.com/maps. (A variety of types of weather maps, including surface, temperature, moisture, wind, cloud cover, precipitation.)

State- or Region-specific Climate Resources

Changes in Streamflow Timing in the Western United States in Recent Decades, by Michael Dettinger, US Geological Survey Factsheet 2005-3018, March 2005, 4 pp., http://pubs.usgs.gov/fs/2005/3018/pdf/FS2005_3018.pdf.

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Climate Change Impacts: The Great Plains, Climate Nexus, http://climatenexus.org/wp-content/uploads/2013/06/ClimateChangeImpactsGP.pdf.

Climate of Idaho, Western Regional Climate Center, http://www.wrcc.dri.edu/narratives/IDAHO.htm.

Climates of the States, *Climatography of the United States* 60, US Climate Normals, NOAA Satellite and Information Service, http://hurricane.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl?directive=prod_select2&prodtype=CLIM60&subrnum=.

Our Changing Climate: Great Plains, National Climate Assessment, http://nca2014.globalchange.gov/report/regions/great-plains.

Our Changing Climate: Northwest, National Climate Assessment, http://nca2014.globalchange.gov/report/regions/northwest. (Includes Idaho.)

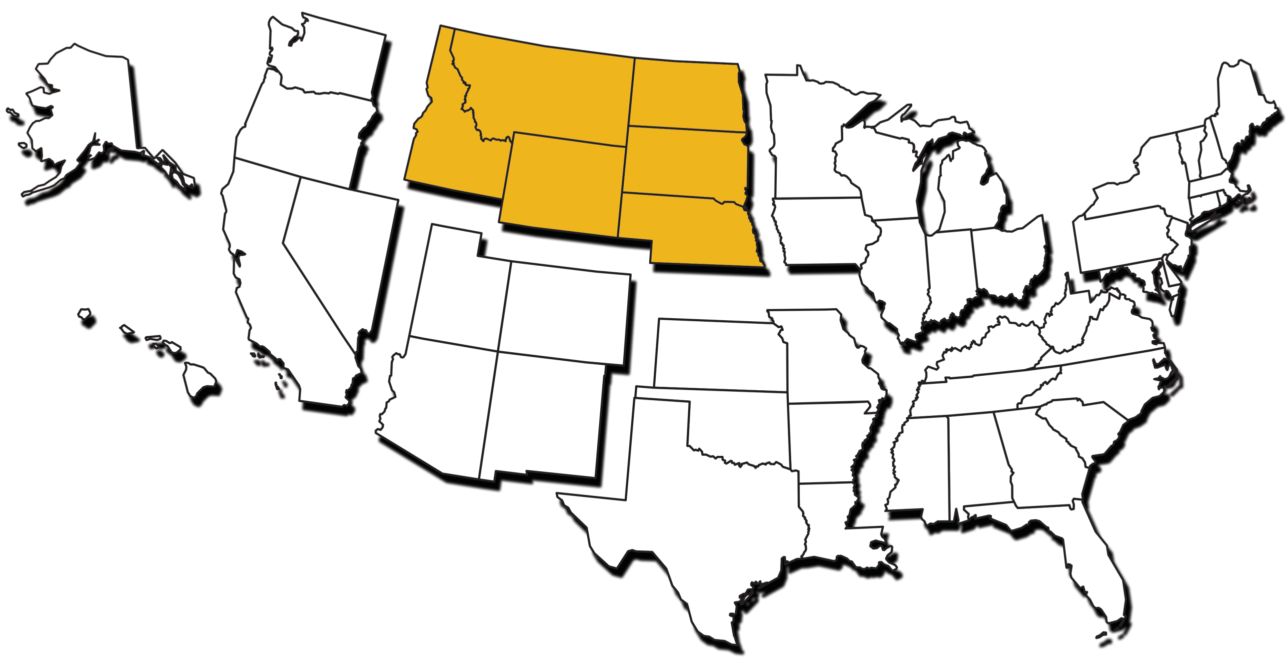
The Paleontology Portal, http://paleoportal.org/. (North American fossil record and geologic and climate histories, by state.)

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 4. Climate of the U.S. Great Plains, by K. E. Kunkel, L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, M. C. Kruk, D. P. Thomas, M. Shulski, N. Umphlett, K. Hubbard, K. Robbins, L. Romolo, A. Akyuz, T. Pathak, T. Bergantino, and J. G. Dobson, 2013, NOAA Technical Report NESDIS 142-4, 82 pp., http://scenarios.globalchange.gov/regions/great-plains.

Weatherbase, http://www.weatherbase.com/weather/state.php3?c=US&s=&countryname=United-States. (Monthly averages and forecasts for cities for each state.)

The Teacher-Friendly Guide™

to the Earth Science of the Northwest Central US



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On the back cover: Blended geologic and digital elevation map of the Northwest Central US. Each color represents the age of the bedrock at the surface. Adapted from Barton, K.E., Howell, D.G., Vigil, J.F., *The North America Tapestry of Time and Terrain*, US Geological Survey Geologic Investigations Series I-2781, http://pubs.usgs.gov/imap/i2781.