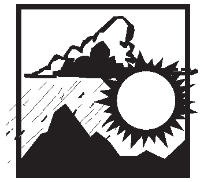

Chapter 9: Climate of the Western US

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—for example, San Francisco—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 of course it can also refer to millions of years.

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 its great variety of environments, from the **boreal** areas of Alaska to the subtropics of Hawai‘i, residents of the West generally have a diverse wardrobe. The most variable climates, however, are in the interior areas and mountains of the western continental US. These areas can vary from frigid in the winter to scorching in the summer. By contrast, coastal climates have only moderate seasonal variation, while Alaska is always cool and Hawai‘i is always warm. The West’s climate is also extremely variable with respect to moisture, from the arid deserts of Nevada to the rainforests of western Washington.

Past Climates

Climate, like other parts of the Earth system, is not static but changes over time, on 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. What is now the West has been tropical or temperate through most of its history, 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

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.*

boreal • *a cold temperate region relating to or characteristic of the sub-Arctic climatic zone.*

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.*

fossil • *preserved evidence of ancient life.*

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history of the Earth's climate, and that of the West. Unfortunately, we do not have as clear an understanding of climate 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, 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 will never be repeated. 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 the 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**

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

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

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

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 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 rearranging 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.

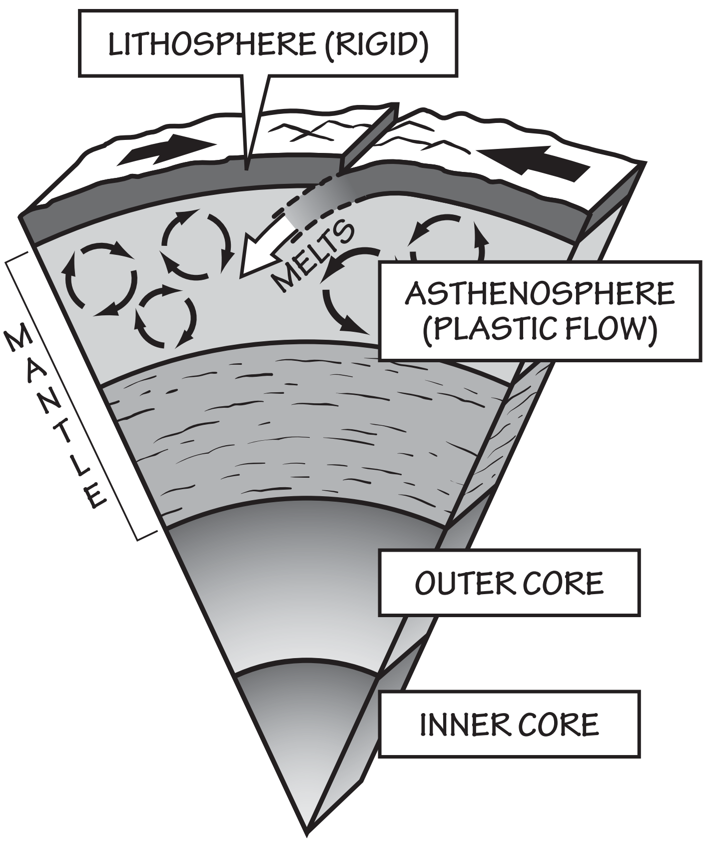


Figure 9.1: The layers of the Earth include the rigid crust of the lithosphere, which is constantly moving over the plastically flowing asthenosphere.

Nearly one billion years ago, the Earth began fluctuating between warm and cool periods lasting roughly 150 million years each. During the cool periods, there is usually persistent ice at the poles; during the 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 much hotter for much of its history (*Figure 9.2*). Through the shifting global climate and the movement of the tectonic plates, parts of what is now the West have at times been at the bottom of a shallow sea, a collection of islands scattered across a

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

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

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.*

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

tropical ocean, a coastal plain with swamps and rivers, covered with ice, and wracked by great floods.

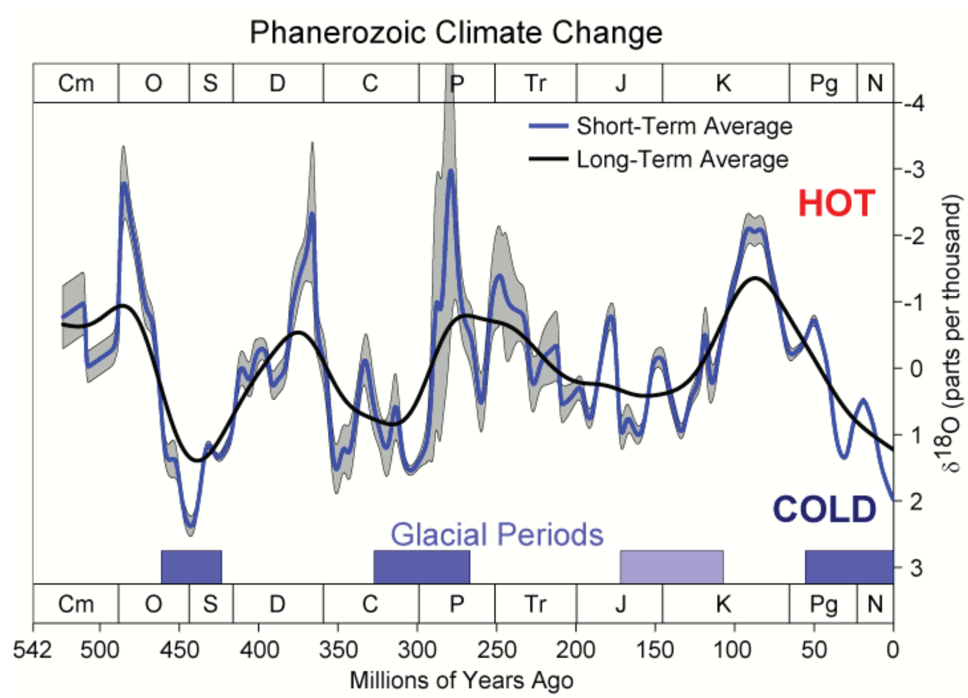


Figure 9.2: Changing global climate throughout the last 542 million years. These data were compiled using the ratios of stable oxygen isotopes found in ice cores and the carbonate skeletons of fossil organisms. (See TFG website for full-color version.)

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 towards a series of cooling feedbacks and caused ice to spread from pole to pole.

See Chapter 6: Glaciers to find out more about glaciations.

An ice-covered planet would remain that way 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. These gases

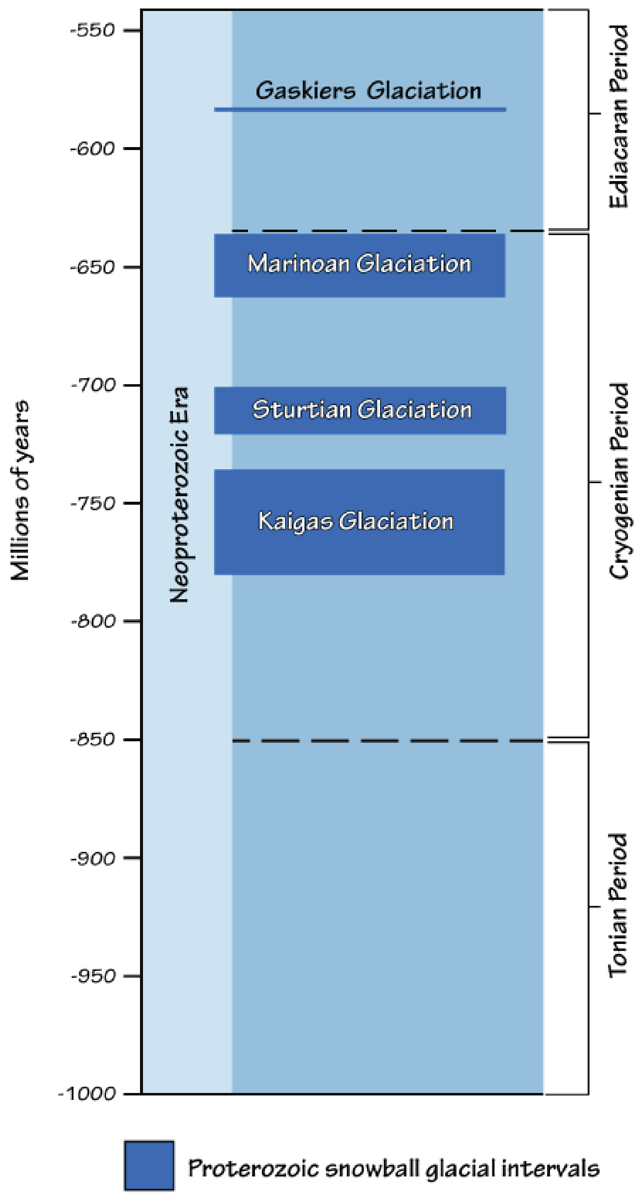


Figure 9.3: Snowball Earth periods during the Proterozoic.

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).*

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

are usually removed from the atmosphere by organisms and the weathering of rocks, but this was not possible through miles of ice! After millions of years, the concentrations of methane and carbon dioxide 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 the warming feedbacks began. Because the oceans had been covered, nutrients 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 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 continental crust that was to become North America, including some of the West, drifted around the surface of the Earth.

9 Climate

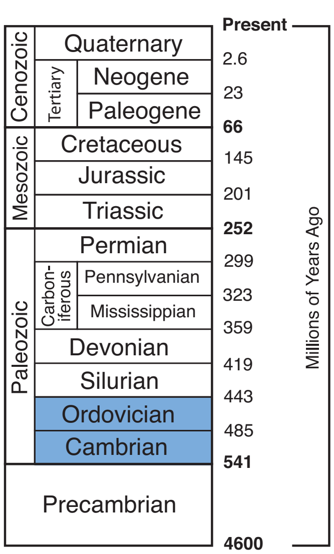
Past

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

trilobite *• an extinct marine invertebrate animal characterized by a three-part body and a chitinous exoskeleton divided longitudinally into three lobes.*

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.*

archaeocyathid *• a vase-shaped organism with a carbonate skeleton, generally believed to be a sponge.*



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 that are 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 North American portion of Rodinia was near the equator, and there were two more Snowball Earths during this time. The fact that North America was at such a low latitude, yet had **glaciers**, is strong evidence that the Earth really did freeze over completely. There is no direct evidence for these events in the West, although some evidence can be found in the rocks of Idaho.

Life and Climate

By 635 million years ago, the Earth had warmed again, and the North American continent moved towards the equator. Throughout much of the **Paleozoic**, North America's terrestrial margin ran through Idaho, Arizona, and easternmost Utah, with the continental shelf extending out through California, Oregon, and Washington (*Figure 9.4*). The West had a warm climate, and fossils such as **trilobites**, **brachiopods**, and **archaeocyathids**--**extinct reef** formers—found

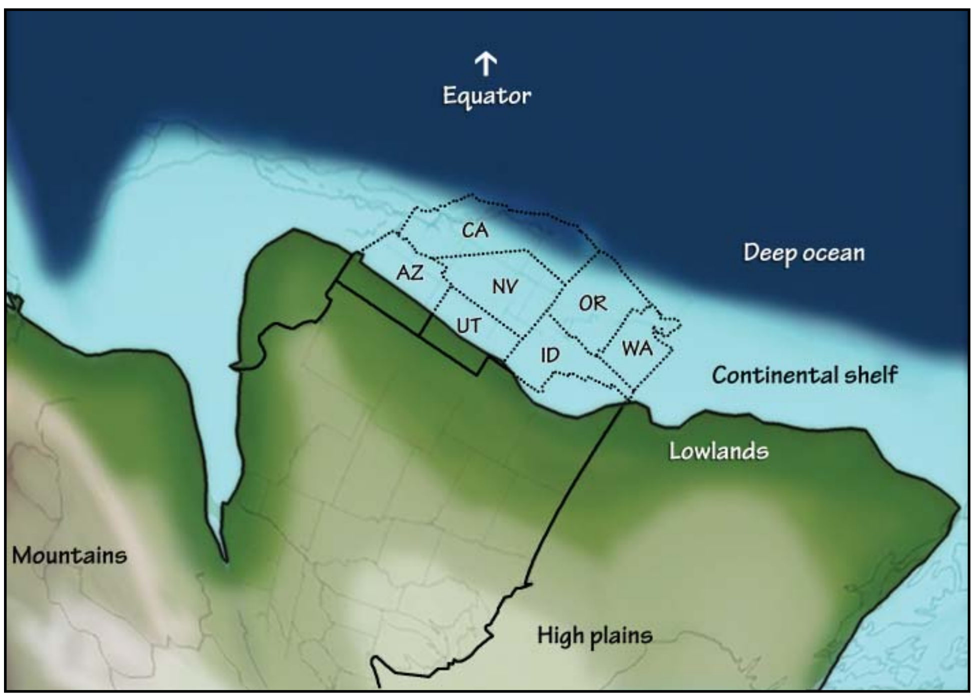


Figure 9.4: The Western United States at 600 million years ago. The entire continent is located in the southern hemisphere, near the equator.

in eastern California and Nevada provide evidence of warm, shallow seas. Sea level rose in the **Ordovician**, and both deep- and shallow-water marine deposits are known from that time. **Conodonts** and **graptolites** are found in deep-water deposits from northeastern Washington and shallow-water marine rocks throughout Nevada and southeastern California, revealing that the climate remained warm during the Ordovician. At the end of the Ordovician, from 460 to 430 million years ago, the Earth fell into another ice age, but corals found in California indicate it remained warm enough for tropical seas to exist there. **Silurian**-age rocks tell us much the same story.

See Chapter 3: Fossils to learn more about fossils of the West's ancient seas.

Alaska is almost entirely composed of ancient **terranes** and **volcanic island** arcs that drifted together at different times during Earth's history and had not assembled into anything resembling modern Alaska until the **Jurassic**. Most of these terranes appear to have experienced warm, wet climates, and geologists have concluded that they all originated in tropical areas of what is now the Pacific Ocean. Alaska's **Cambrian**- through Silurian-age rocks all formed on these tropical **microcontinents**. This is also true for much of central and western Washington, all of Oregon, and most of northwestern California, which formed in a similar manner as terranes and island arcs **accreted** onto the edge of the continent at its **subduction** zone.

From 430 to 300 million years ago, North America moved north across the equator, and the cycle of warming and cooling was repeated yet again. In the **Devonian**, sea level was higher than it had been earlier, but despite this, Devonian rocks are relatively scarce in the West, with small areas widely scattered across Nevada. The most extensive outcrops of Devonian rocks are located on the tropical accreted terranes, and include some very large reefs. Devonian rocks are also common in northern Alaska. These rocks include **carbonate** platforms, which are consistent with a low-latitude position and warm climate.

By the Early **Carboniferous**, ice capped the South Pole and began to expand northward. Although the Earth's temperature fell during this time and the frozen water far to the south caused sea levels to drop, the West still remained relatively warm because of North America's low-latitude position. Mountain building in Nevada raised the sea bottom, dividing the marine environment into shallow water to the east and deep water to the west. Nevada's shallow-water deposits contain reefs, indicating that the climate there was still warm. Later, in the **Permian**, these shallow areas became beaches and lagoons as sea level dropped. Carboniferous and Permian rocks in Oregon, northern California, western Washington, and Alaska originated on tropical terranes—some contain lush, tropical floras that are completely dissimilar to those on the main part of the continent, a testament to their continued isolation in the ocean far from the West (which had now become part of the supercontinent **Pangaea**). Carboniferous rocks in northern Alaska contain extensive carbonate platforms, which are indicative of a warm climate. Alaska's Permian rocks are also indicative of a marine environment.

Around 220 million years ago, the West moved north from the equator. Pangaea, a supercontinent composed of nearly all the landmass on Earth, began breaking

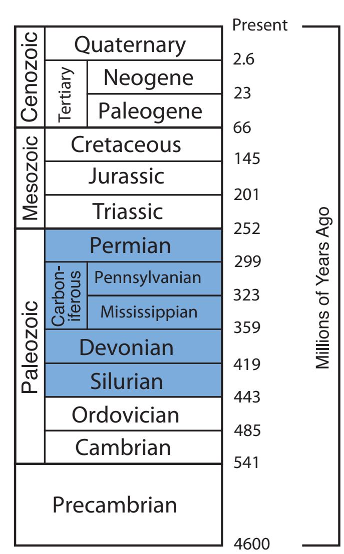
Past

conodonts *• extinct, eel-shaped animals classified in the class Conodonta and thought to be related to primitive chordates.*

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

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

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



Past

ichthyosaurs *• extinct Mesozoic marine reptiles that were probably similar in size and habitat to the toothed whales, dolphins, and large sharks of today.*

oil *• see petroleum: a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons*

ginkgo *• a terrestrial tree belonging to the plant division Ginkgophyta, and characterized by broad fan-shaped leaves, large seeds without protective coatings, and no flowers.*

up into continents that would drift toward their modern-day positions (*Figure 9.5*). The Earth remained warm until worldwide temperatures began to dip again, around 150 million years ago. At this time, the West was still largely underwater, but the Sierra Nevada Mountains had begun to form as a volcanic island arc close to the edge of the continent. Nevada's **Triassic** rocks contain both deep-water marine and terrestrial deposits—its Triassic seas were rich with **ichthyosaurs** and other marine reptiles, while its terrestrial rocks reflect the aridity and seasonality of the climate farther inland. As mountain building continued into the Jurassic, the seas became shallower, while terrestrial deposits expanded. By this time, terranes were beginning to collide with the continent—some of these collisions included volcanic islands ringed with corals, indicating that the climate remained warm. Similar island arcs formed close to what is now southern Alaska, where a very productive sea flooded the Triassic continental margin. The organic-rich rocks that formed in this sea are some of the most prolific source rocks for **oil** on Alaska's North Slope.

See Chapter 7: Energy for more information about the production and use of oil in Alaska.

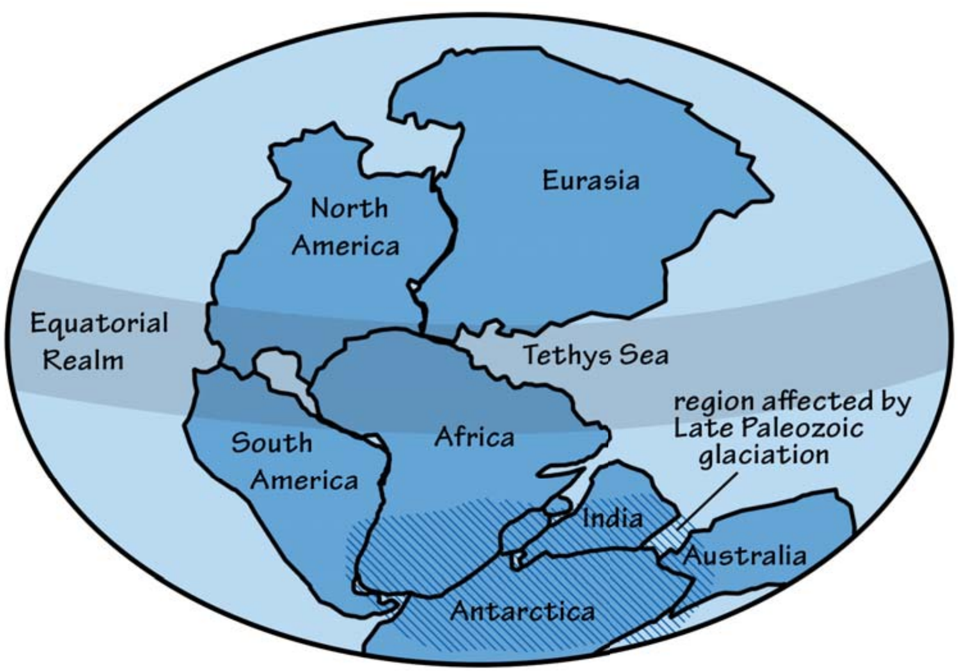
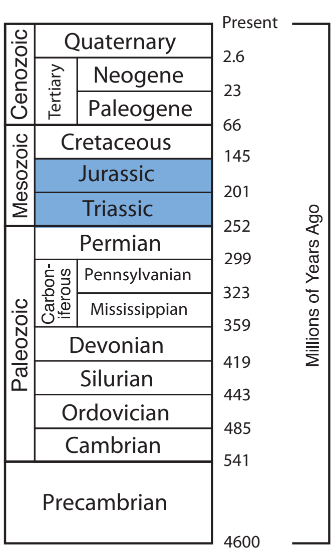


Figure 9.5: The break up of Pangea began around 220 million years ago.

Jurassic rocks are widely scattered through Oregon and Washington, where they contain coral-ringed volcanic arcs with associated deeper marine sediments. Jurassic rocks in California reflect both shallow-water marine and terrestrial environments. A large area of shallow-water marine deposits was laid down just off of the rising Sierra Nevada, in what is now the eastern Central Valley. The



Past

terrestrial rocks of southeastern California contain **ginkgos** and **cycads** that indicate a warm, moderately wet climate. Terrestrial Jurassic rocks in southern Nevada, however, show that the climate on land was still arid. Meanwhile, much of southern Alaska was assembled during the Jurassic as a series of island arcs and terranes collided with northern Alaska, which had now drifted into its current position and existed as a broad, flat shelf of shallow marine rocks.

The Earth warmed near the beginning of the **Cretaceous**, and sea level rose. Mountain building continued throughout the West with the formation of both the Sierra Nevada and the Rocky Mountains. **Erosion** predominated, and Nevada and Oregon have a very sparse record of Cretaceous sedimentation and climate; the few outcrops from this time period show that Nevada was terrestrial and Oregon was still largely marine. Washington has a slightly better record, showing that it too was still principally marine. Global climate was warm, but reefs did not form, probably due to the intense mountain building and erosion that shed a great amount of sediment into the interior embayments and the Pacific Ocean. Even though Alaska was closer to the North Pole than it is at present, fossil vegetation indicates that its climate was very similar to that of western Oregon today. Lush swamps and forests occupied lowland areas, and some swamps had become rich **coal** beds.

The climate cooled again at the end of the Cretaceous, 65 million years ago. This cooling had the greatest impact on northern Alaska, where fossilized forests resemble those found near Anchorage today. But after the end of the Cretaceous, the climate warmed once more—by around 50 million years ago, the West's climate was actually hot, with palm trees growing in southern Alaska! Alaska's northern forests once again grew to resemble those of modern forests much farther south. The sea withdrew from most of Oregon and Washington, and plant fossils are abundant throughout these states. One of the best records of the West's Cretaceous climate is found in Oregon's John Day fossil beds. Here, plant and animal fossils indicate that from 50 to 35 million years ago this area was home to a subtropical rainforest with banana and citrus trees. Fossil floras in western and north-central Washington tell a similar story, and palm trees were abundant. Between 35 and 20 million years ago, however, the climate became cooler and drier, and prairies and deciduous trees such as oak, maple, and alder flourished. This coincided with the initial **uplift** of the Cascade Range (37–7 million years ago), which began to create a rain shadow (*Figure 9.6*) to the east. The final uplift of the Cascades and Sierra Nevada created the intense rain shadow that is responsible for the aridity of eastern Washington, eastern Oregon, and Nevada today. Moist Pacific Ocean air moves eastward with the prevailing **winds**, and it 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 it warms as it moves down the eastern side of the mountain range, promoting evaporation.

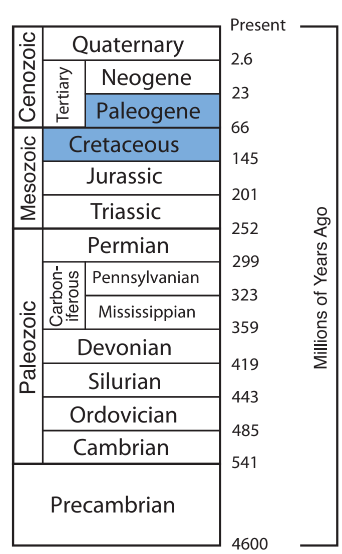
See chapter 3: Fossils for more about plants of the prehistoric West.

cycad *• a palm-like, terrestrial seed plant (tree) characterized by a woody trunk, a crown of stiff evergreen leaves, seeds without protective coatings, and no flowers.*

erosion *• the transport of weathered materials.*

coal *• a combustible, compact black or dark-brown carbonaceous rock formed by the compaction of layers of partially decomposed vegetation.*

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



9 Climate

Past

basalt • *an extrusive igneous rock, and the most common rock type on the surface of the Earth.*

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

lava • *molten rock located on the Earth's surface.*

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

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.*

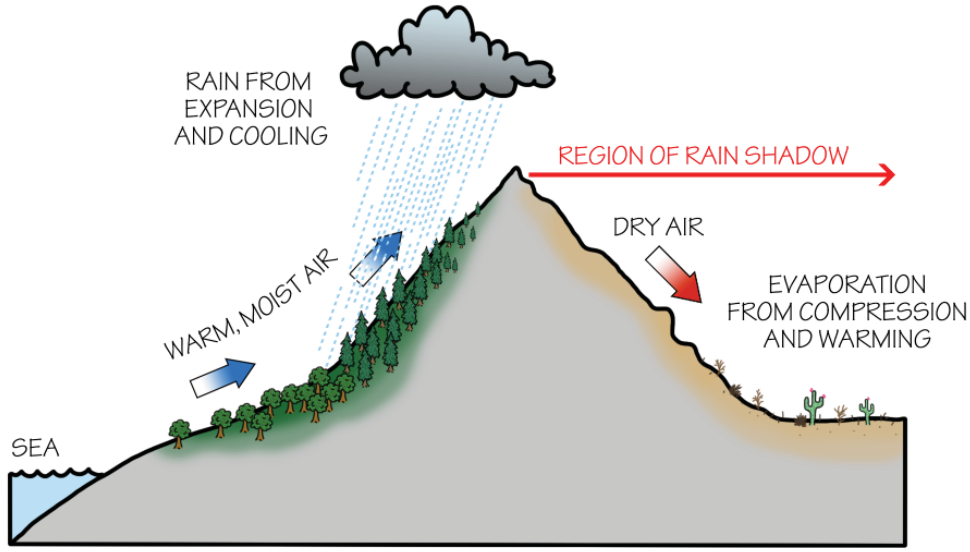


Figure 9.6: The key characteristics of a rain shadow.

Late in the **Cenozoic**, eruptions in eastern Oregon produced enormous amounts of **basalt** that flowed north and west, filling the Columbia River basin. These are some of the largest such eruptions in the history of the Earth, and they took place several times over a span of about 11 million years. While evidence that these eruptions influenced global climate is ambiguous, climatic changes are recorded in **soils** that formed atop some of the **lava** flows. These soils indicate a decrease in temperature after a period known as the Middle **Miocene** Climatic Optimum, a brief warming episode that occurred around 16 million years ago.

See Chapter 2: Rocks to learn more about the Columbia Flood Basalts.

Since 800,000 years ago, an equilibrium appears to have been reached between warming and cooling, with Earth's **ice caps** growing and retreating primarily due to the influence of astronomical forces. During the **last glacial maximum**, ice covered the northern part of Washington State (*Figure 9.7*). The ice sheet did not extend into central or northern Alaska since the local climate was very dry, though an ice cap covered the Brooks Range. During periods of ice advance, the West was colder than it is today, with extensive mountain glaciers occurring throughout the region; in fact, Yosemite Valley was carved out at this time. Microfossil evidence from the Rancho La Brea Tar Pits in Los Angeles tells us that southern California's climate around 40,000 years ago was similar to San Francisco's today.

See Chapter 3: Fossils for more on the Rancho La Brea Tar Pits.

Around 12,000 years ago, all of Washington east of the Cascades was inundated and scoured by numerous enormous, violent floods. These occurred when an ice sheet alternately blocked and retreated from what is now the Clark Fork River in northwestern Montana and northern Idaho. When the river was

Past

hot spot • *a volcanic region thought to be fed by underlying mantle that is anomalously hot compared with the mantle elsewhere.*

windward • *upwind; facing into the prevailing winds, and thus subject to orographic precipitation.*

Figure 9.7: The maximum extent of the Cordilleran and Laurentide ice sheets across western North America and Alaska.

blocked, an enormous lake—Glacial Lake Missoula—built up behind the ice dam. When the ice dam later failed, the water was released catastrophically. These floods cut through the dust deposits and basalt that covered much of the region, leaving islands, escarpments, and channels so large that ground-based geologists did not at first recognize their origins.

The Hawaiian Islands began to form 11 million years ago, although most are younger than 7.5 million years. These islands formed from volcanoes erupting from the sea floor over what geologists call a **hot spot**. Hawai'i has a poorly preserved paleoclimate record, probably because the landscape has been so active, with continuous volcanic eruptions and new lava flows covering the landscape as well as intense erosion occurring on the wetter, **windward** sides of the islands. Because of the

See Chapter 8: Soils to learn more about the soils of Hawai'i.

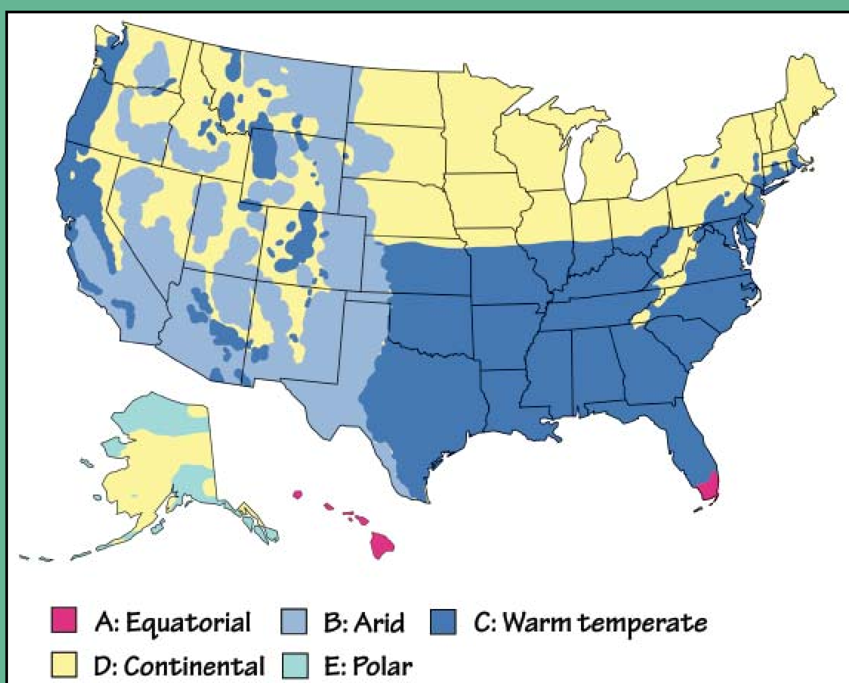
islands' latitudinal position, geological records found in the nearby deep sea, and the nature and depth of the soils formed on the long-exposed lava, we know that Hawai'i's climate has always been tropical to subtropical.

Present Climate of the Contiguous Western States

Because of its wide latitudinal range, the proximity of the Pacific Ocean, and the presence of long, north-south mountain ranges, the Western States have an enormous variety of climatic areas. These include hot, dry deserts in the Basin and Range, a Mediterranean climate along the southern Pacific Border,

The Köppen Climate Map

Wladimir Köppen developed a commonly used system of climate categorization based on the kinds of vegetation that 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.)

rainforests in the northern Pacific Border and Alaska, and tundra in Alaska's far north. Even individual states can have tremendous diversity—depending on which of the many **Köppen system** maps you refer to, the state of Washington alone contains as many as eight different climate types.

With such diverse climate types, a wide range of temperatures can be experienced throughout the West (*Figure 9.8*). Generally, temperatures tend to decrease northward (and also from west to east), with cooler temperatures at higher elevations and across the West's north-south mountain ranges. Temperatures in coastal areas are moderated by the Pacific Ocean and, in the northwest, by the Rocky Mountains, which prevent cold Arctic air from reaching the coast. Average lows and highs in Southern California range from 3° to 46°C

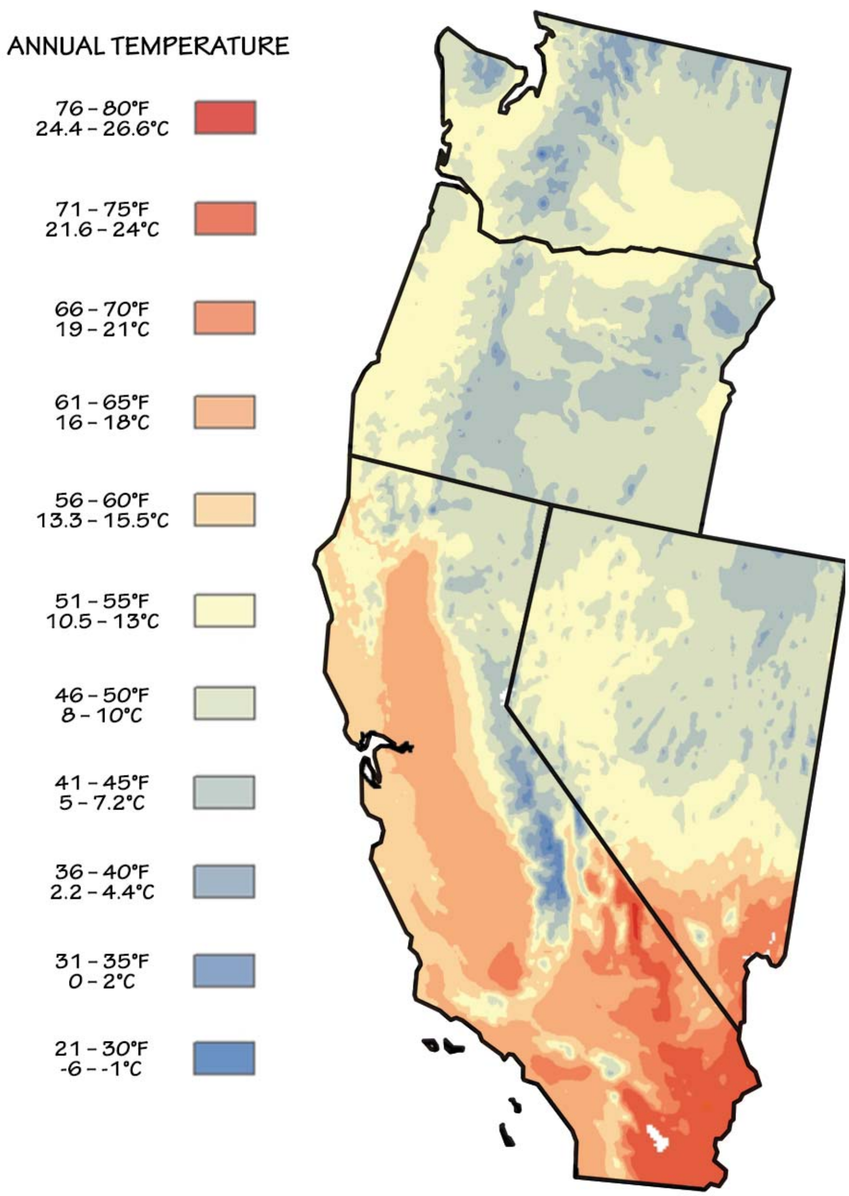


Figure 9.8: Mean annual temperature for the contiguous Western states. (See TFG website for full-color version.)

Present

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

(37° to 114°F) inland in Death Valley and 9° to 24°C (49° to 76°F) on the coast in San Diego. Statewide average lows and highs in Oregon run from -3° to 28°C (26° to 82°F), while in Washington, temperature ranges from -1° to 32°C (29° to 89°F). Nevada experiences average temperatures spanning from 4° to 40°C (39° to 104°F)

The West's spectacular mountain ranges (apart from those in Alaska) run from north to south. These ranges—the Coastal Range, the Cascades, the Rockies, and the Sierra Nevada—create a pronounced east-west precipitation gradient across the Western states. The overall effect is to produce dry rain shadows on the eastern sides of the West's mountain ranges, and wet areas on the western sides (*See Figure 9.6*). This effect is most pronounced from Northern California up through Washington, since the **jet stream** is often located over this area—especially in winter—and brings moist ocean air inland. As an example of how extreme this precipitation gradient can be, Olympic National

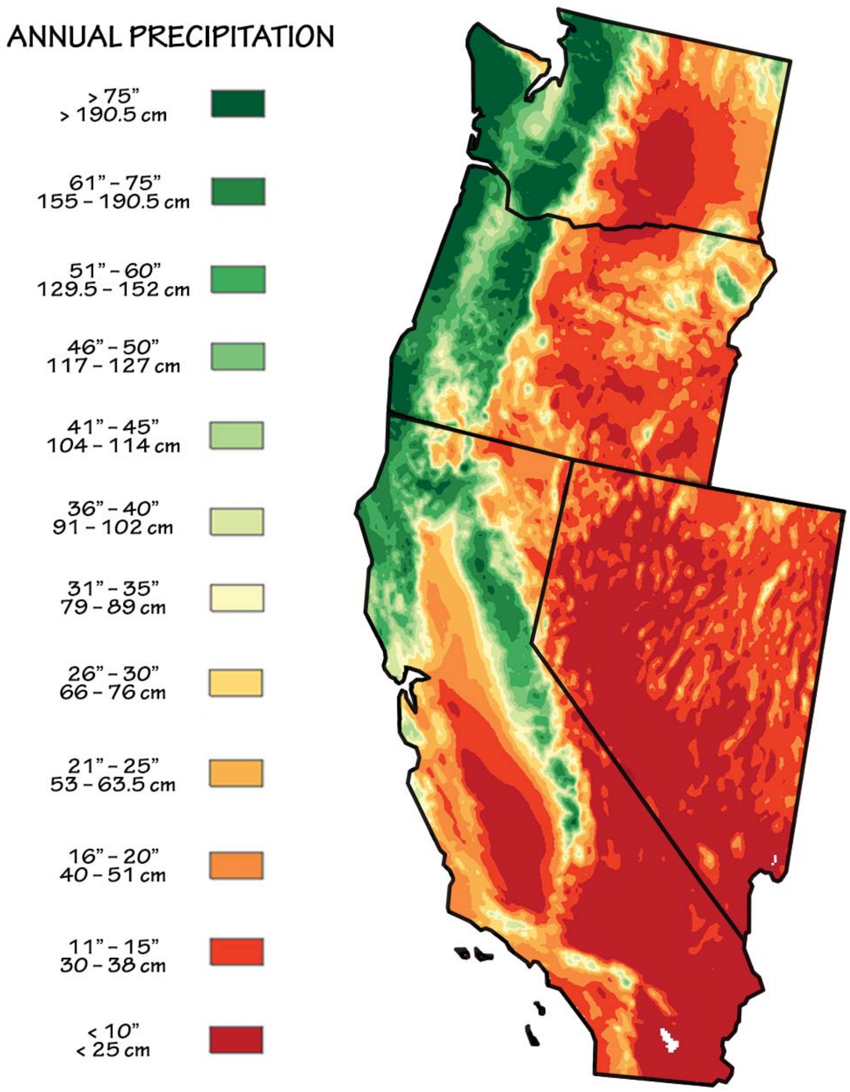


Figure 9.9: Mean annual precipitation for the West Coast. (See TFG website for full-color version.)

Park in Washington receives over 190 centimeters (75 inches) of rain annually on average, whereas communities only 400 kilometers (250 miles) to the east in Washington receive only 18 to 20 centimeters (7 to 8 inches) annually. As the most arid state in the US, Nevada receives only about 24 centimeters (9.5 inches) of rainfall a year (*Figure 9.9*).

Present Climate of Alaska

Alaska's climate, like that of other parts of the West, is influenced by its mountain ranges and its proximity to the ocean. Statewide averages range from a low of -20°C (-4°F) in January to a high of 11°C (52°F) in July (*Figure 9.10*). North of

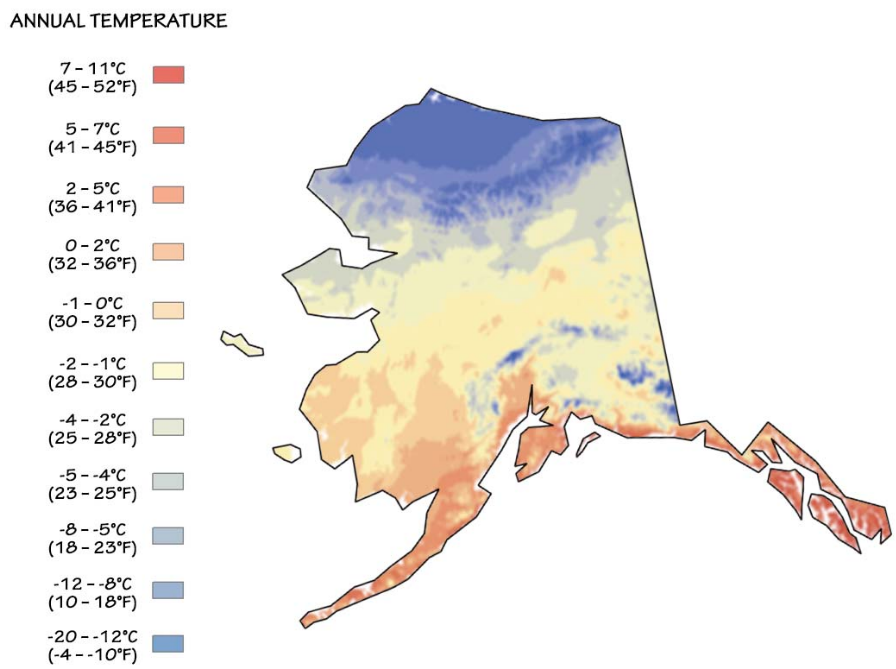


Figure 9.10: Mean annual temperature for Alaska. (See TFG website for full-color version.)

the Brooks Range, Alaska has a cold, dry, polar climate with frequent winter blizzards. Temperatures on the coast are moderated somewhat by the Arctic Ocean. Central Alaska has a dry continental climate, with a large variation between summer and winter temperatures. For example, the town of Takotna in Alaska's interior has an average low temperature of -27°C (-17°F) in January and an average high of 22°C (72°F) in July.

A third climate area exists in the Alaskan southeast, south coast, and southwestern islands, and in west-central Alaska in the summer. These areas have moderate temperatures—an average annual temperature of about 7°C

(45°F)—and high precipitation. Some areas are home to lush rainforests and receive around 500 centimeters (200 inches) of rain a year (*Figure 9.11*). The climate in west-central Alaska is influenced by a phenomenon that is unique in

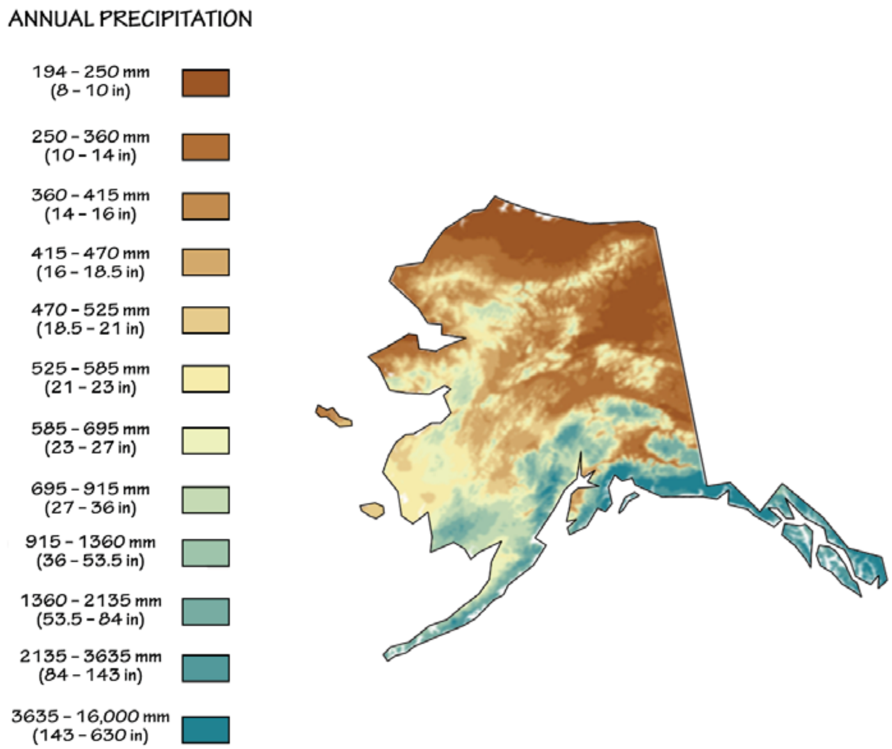


Figure 9.11: Mean annual precipitation for Alaska. (See TFG website for full-color version.)

the United States: the seasonal presence of sea ice. In the winter when sea ice covers the Bering Sea, this area loses the moderating effect of open water and has a continental climate. When the sea ice melts in summer, the climate returns to a warmer, more humid maritime state.

Figure 9.12: Melting permafrost has caused a house in Shishmaref, Alaska to topple; on the Alaska Highway, permafrost subsidence caused the road to collapse under the weight of a pickup truck.

The lives of the West's residents are tied to climate in critical ways. People in Southern California's coastal area and Central Valley enjoy a pleasant climate, but they depend on water from elsewhere—mostly from snowmelt—for their everyday needs and for agricultural irrigation. At the time of this writing in 2014, California is in the midst of an extreme drought, and 10% of the state is in exceptional drought, the most severe possible. In Alaska, infrastructure such as roads, buildings, and oil pipelines built on **permafrost** is vulnerable to a warming climate, since the land surface develops bumps and pits when permafrost melts (*Figure 9.12*). Climate is also linked to energy resources—in the Pacific Northwest, the combination of **topographical** variation and abundant precipitation creates an ideal environment for hydropower.

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.*

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

trade winds • *a major tropical wind system, involving the flow of high-pressure subtropical air to the low-pressure equatorial zone.*

Present Climate of Hawai‘i

The eight main Hawaiian Islands stretch between 19° and 22° north latitude. This places them within the tropics, and also within the belt of persistent northeast **trade winds** (*Figure 9.13*). This geography, combined with the high topography of many Hawaiian peaks, gives rise to large variations in climate across the islands—Hawai‘i Island alone has some of the most extreme climate gradients of any place on earth.. Additionally, as half of the land area of Hawai‘i lies within eight kilometers (five miles) of the ocean, the ocean is an important control on climate.

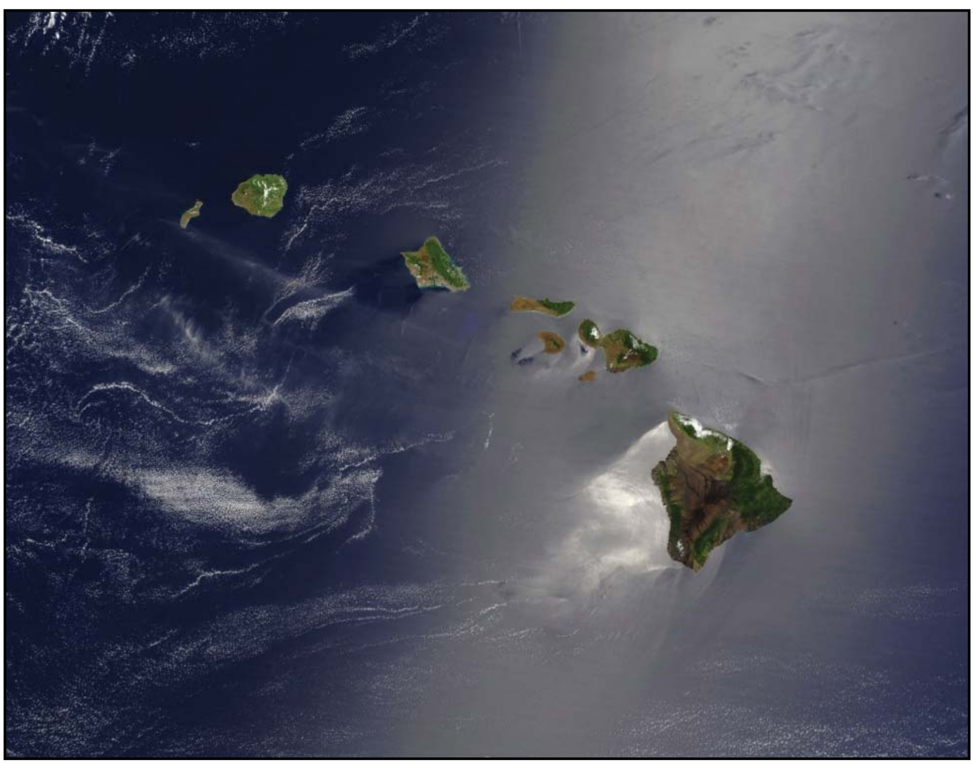


Figure 9.13: The effect of the northeast trade winds is seen in the shiny, highly reflective, calm water southwest of Hawai‘i Island, where the ocean lies in the lee of the island's big volcanoes.

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

Effect of the Ocean

Hawai‘i is a small archipelago in the center of the world’s largest ocean. Water has a very high **heat** capacity (i.e., a lot of energy is required to raise the temperature of water). This means that the annual temperature variation of the ocean is small. Around the Hawaiian Islands the ocean surface temperature falls between 24°C (75°F) in winter and 27°C (81°F) in summer. The seasonal variation in land surface temperature for coastal Hawai‘i is similar, about 5°C (9°F) from winter to summer. In a continental setting the seasonal land temperature variation would be much larger; for example, in Chicago the seasonal variation is 25°C (45°F). Thus the ocean dominates climate in Hawai‘i’s coastal areas.

Effect of Latitude

As mentioned earlier, Hawai‘i lies between 19° and 22° north latitude, just south of the Tropic of Cancer. At this latitude, the global circulation of the atmosphere plays a significant role in climate. Incoming sunlight warms the Earth’s surface, and it does so year-round at equatorial latitudes. The air directly above the surface is warmed and rises. The rising air expands and then cools, allowing water vapor to condense and fall as rain; worldwide equatorial latitudes are therefore characterized by meteorological low pressures and high rainfall (*Figure 9.14*). The rising air also flows poleward when it reaches neutral buoyancy with

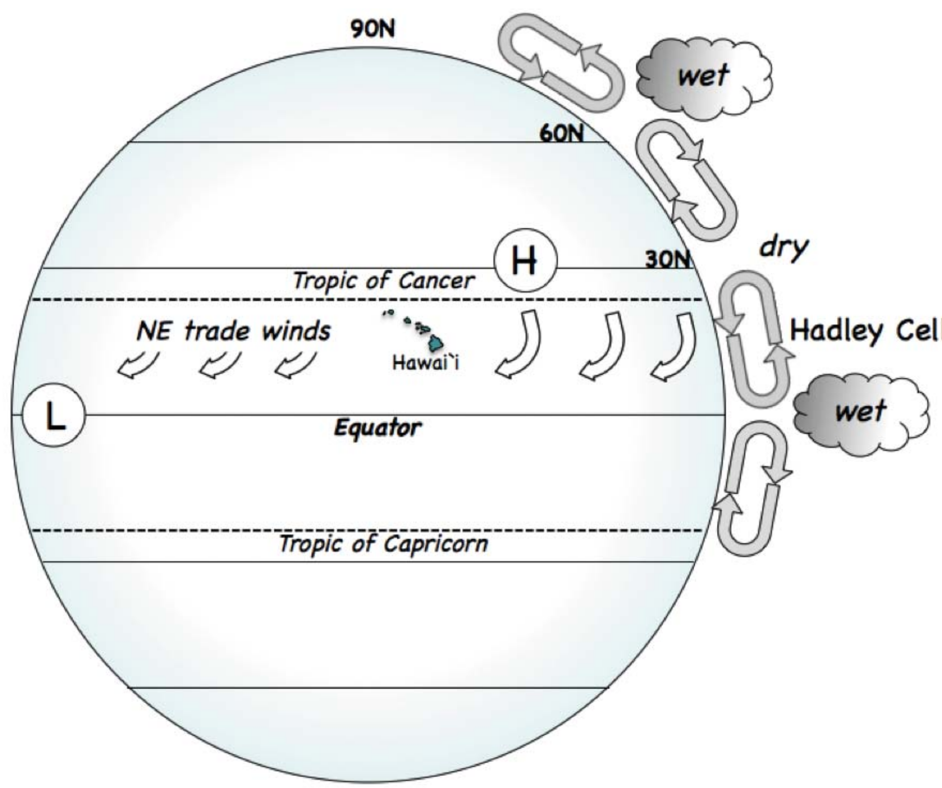


Figure 9.14: Aspects of general atmospheric circulation important for Hawai‘i’s climate. The islands lie within the tropics, in a belt of persistent northeast trade winds, and beneath the descending limb of the Hadley circulation cell. A stable high-pressure system—the North Pacific Anticyclone (H)—remains north-northeast of the islands throughout the year.

its surroundings, where it continues to cool and eventually becomes denser and sinks. This occurs at a latitude of ~30° in both hemispheres. The sinking air is **compressed** and consequently warmed, and so it becomes strongly undersaturated with water vapor and has a low relative humidity. Near the latitudes of 30°N and 30°S are zones of high pressure and exceptionally dry climate, Earth's "desert" latitudes. At the surface, the air completes its circuit by flowing back toward the equator. The surface airflow is deflected westward by the Earth's rotation, creating the trade winds. This circulation pattern is known as a **Hadley cell**—named after 17th century meteorologist George Hadley—and is an important part of atmospheric circulation.

compression • *flattening or squeezing as a result of forces acting on an object from all or most directions.*

Hawai‘i, in the northern tropics, is located beneath the descending limb of the Hadley cell. Thus, the air above the islands warms as it approaches the surface, with a temperature gradient running from warm to cool air with increasing altitude. At the same time, the air heated by contact with the warm earth surface also cools with increasing altitude. Most of the time (80–90% of days) these two cooling trends are not continuous, and there is instead a temperature discontinuity located at an altitude of about 2000 meters (6000 feet). This arises from the more rapid cooling rate of the moist lower air relative to the cooling rate of the dry upper air. This discontinuity is called the **trade wind inversion** (*Figure 9.15*). The inversion is easily seen from any vantage point in the islands, as it creates a ceiling for cloud formation (*Figure 9.16*). Because of this control on cloud position, the inversion also functions as a control on the distribution of rainfall across the islands.

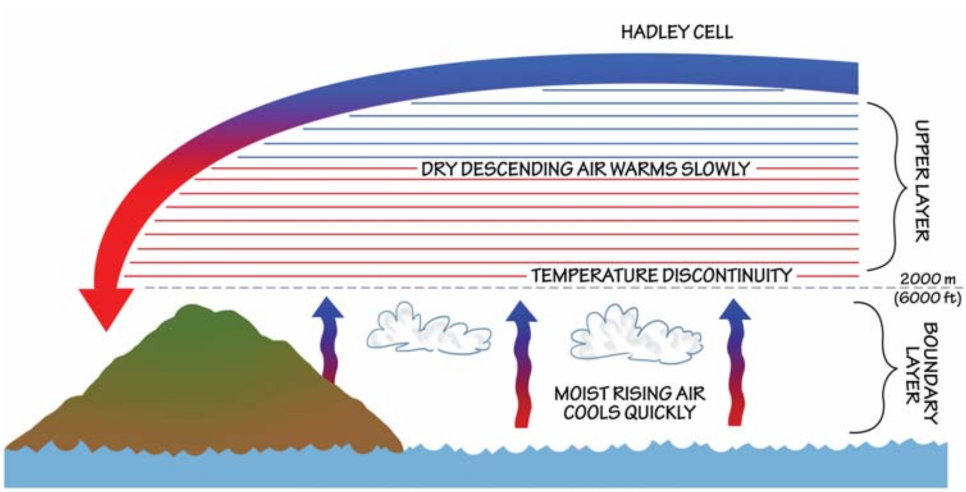


Figure 9.15: The rate of cooling of moist boundary layer air is faster than the rate of warming of dry descending Hadley cell air. The temperature (density) discontinuity prevents boundary layer air from mixing with upper layer air, and so it creates an upper ceiling for cloud formation.
(See TFG website for full-color version.)

relief *• the change in elevation over a distance.*

boundary layer *• the atmospheric layer closest to the surface of the Earth, which has a high relative humidity and is affected by the Earth's heat and moisture.*

leeward *• downwind; facing away from the wind.*

orographic precipitation *• rainfall caused when wind pushes a mass of humid air up the side of an elevated land formation like a mountain.*

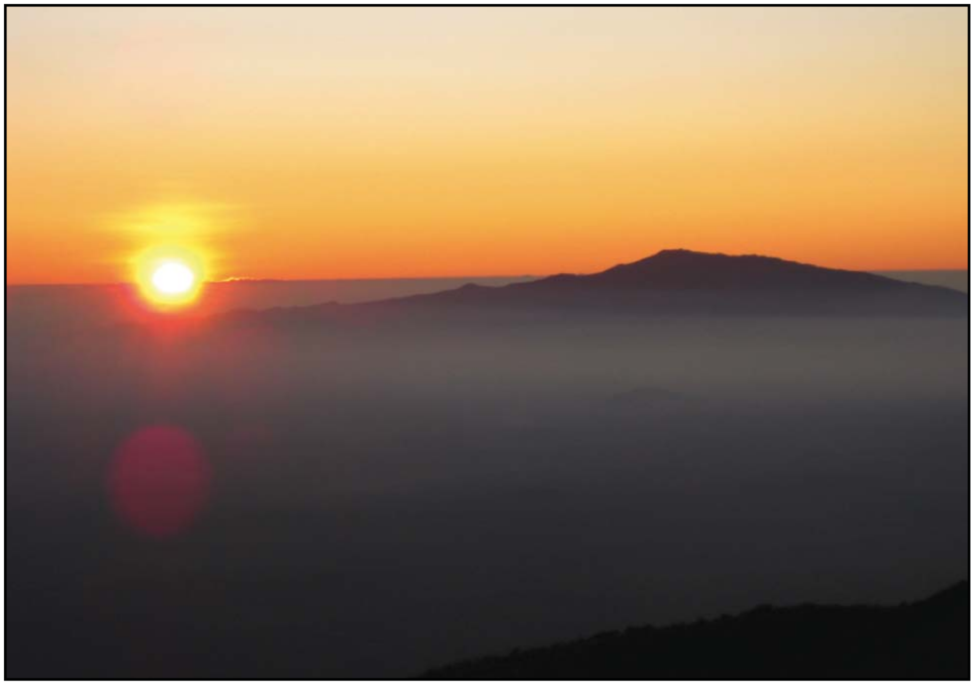


Figure 9.16: Trade wind inversion. The summit of Hualālai, at sunset, rises above the inversion layer while hazy and humid boundary layer air remains below. The Hualālai summit is 2521 meters (8271 feet), and here the inversion is ~1980 meters (~6500 feet).
(See TFG website for full-color version.)

Effect of Topography

The most interesting control on the climate of Hawaiʻi is the high topographic **relief** of the islands. The islands of Hawaiʻi, Maui, Kauaʻi, Molokaʻi, and Oʻahu all have summits that are above 1200 meters (4000 feet) in elevation. On Hawaiʻi Island the peaks of Mauna Kea and Mauna Loa are each above 4180 meters (13,700 feet). Without these summits, Hawaiʻi would be a warm and humid place with relatively low rainfall. However, the presence of these huge mountains changes the local climate dramatically, which, in turn, leads to the great diversity of climate zones found in Hawaiʻi (*Figure 9.17*).

The air above the ocean—the **boundary layer**—has a high relative humidity because it is in contact with the warm tropical ocean. Northeast trade winds carry this moisture-laden air to the Hawaiian Islands. The mountainous islands divert the airflow both around and over the topographic obstructions. Air that rises over the mountains expands and cools, and the moisture acquired from the ocean condenses and rains out. The windward sides of each island are therefore places with frequent and abundant precipitation (*Figure 9.18*). As the air continues down the **leeward** slopes it is at first compressed, and subsequently warms, and no additional moisture condenses; the leeward island shores are therefore very dry. This topography-induced upward airflow creates **orographic precipitation** on windward slopes and a rain shadow on the leeward side. On most of the Hawaiian Islands, the maximum rainfall occurs at 610–910 meters (2000–3000 feet) above sea level, although the two wettest spots in the islands are slightly higher in elevation. Waiʻaleʻale on Kauaʻi (1570 meters [5150 feet]) and Big Bog on Maui (1650 meters [5400 feet]) vie with each other for the title

of wettest spot in the US, and indeed at ~1000 centimeters (~400 inches) of annual rainfall they are two of the wettest spots on Earth.

Areas of high topography are dry, as the trade wind inversion prevents clouds from rising high enough for orographic precipitation to occur there. The high summits and leeward slopes receive most of their annual precipitation during winter storms, when high-altitude, low pressure systems develop in the subtropics. These *kona* (Hawaiian for leeward) storms bring extended periods of rain and even snow (the latter on the summits of Mauna Kea, Mauna Loa, and Haleakalā).

Climate Gradients

Ocean, atmosphere, and topography interact in Hawai‘i to make the islands a land of diverse climate with extreme climate gradients. The maps of rainfall and temperature distribution in Hawai‘i (s*ee Figures 9.17* and *9.18*) clearly show the range and proximity of these variations. On Maui, the distance is only 32 kilometers (20 miles) from Big Bog (the wettest location, with 1029 centimeters [405 inches] per year) to Kihei (the driest, at 28 centimeters [11 inches] per year). On Kaua‘i the distance from the wettest spot, Wai’ale’ale

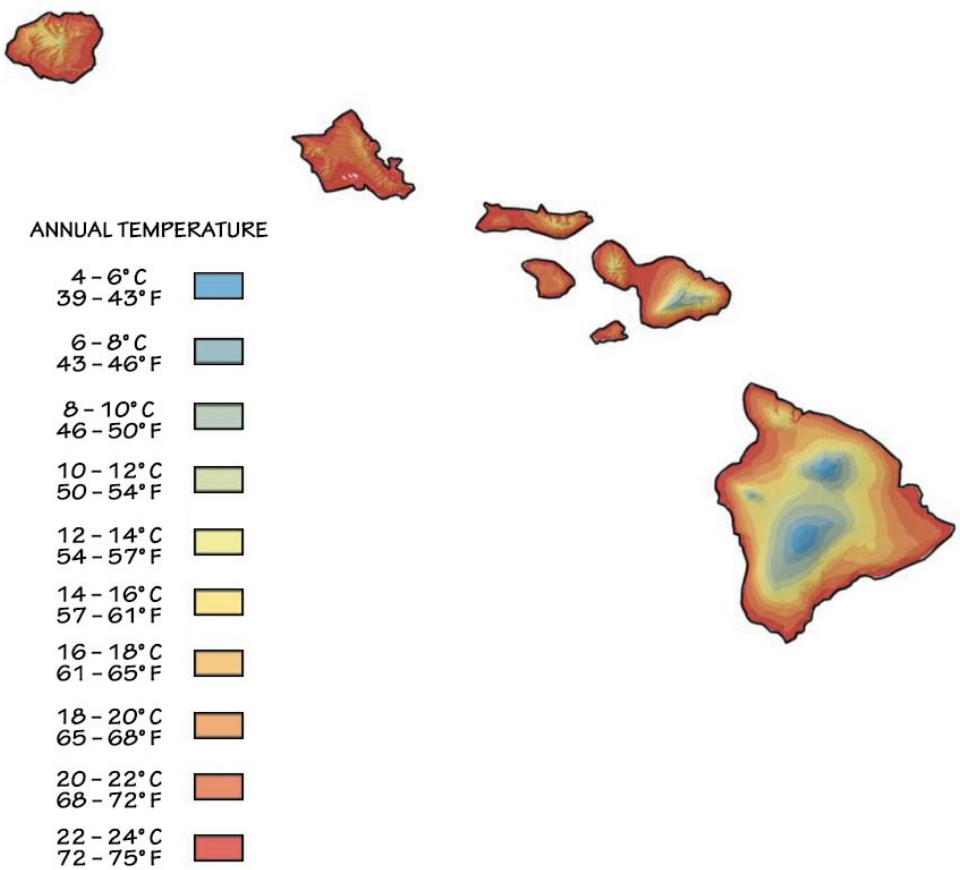


Figure 9.17: Mean annual air temperature in Hawai‘i. Air temperature is inversely related to elevation. Thus the temperature variations map large-scale topographic features as well. (See TFG website for full-color version.)

parent material • *the original geologic material from which soil formed.*

endemic • *native to a particular geographic area or range.*

sustainable • *able to be maintained at a steady level without exhausting natural resources or causing severe ecological damage, as in a behavior or practice.*

moraine • *an accumulation of unconsolidated glacial debris (soil and rock) that can occur in currently glaciated and formerly glaciated regions.*

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

(1143 centimeters [450 inches] per year) to the driest spot, Polihale Beach (46 centimeters [18 inches] per year), is only 26 kilometers (16 miles). This gives Kaua‘i a rainfall gradient of 38 centimeters per year per kilometer (24 inches per year per mile). Superimpose this gradient onto New York City, with its rainfall level of 127 centimeters (50 inches) per year: could we imagine a desert just three kilometers (two miles) west of Central Park?

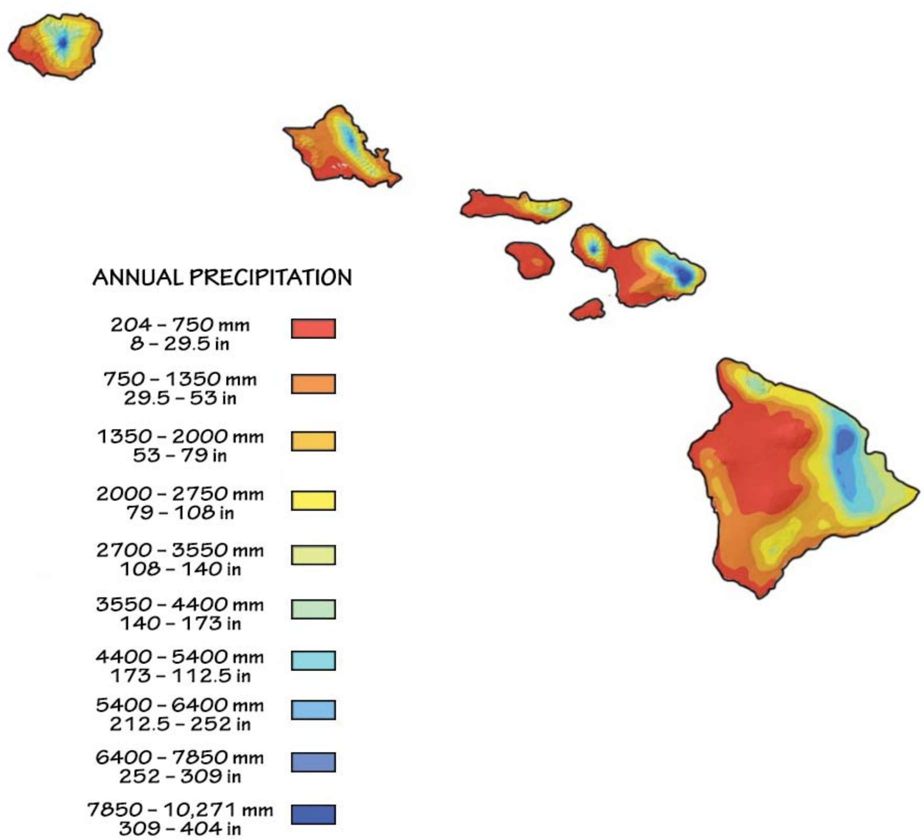


Figure 9.18: Mean annual rainfall in the Hawaiian Islands. Northeast trade winds combine with topography to create a strongly asymmetrical rainfall distribution. Leeward (west) areas receive little rainfall while windward (east) slopes are some of the wettest places on Earth. (See TFG website for full-color version.)

Large changes over short distances characterize the Hawaiian Islands and drive natural processes as well as human activity. Rates of weathering and erosion are much higher in areas of high rainfall. Therefore the islands' windward slopes are more deeply incised by stream erosion. In dry areas erosion rates are lower; however, episodic winter storms can lead to large sediment loads discharged to the ocean from arid areas with little vegetative cover. Sedimentation events have a negative impact on coral reefs, as the corals require clear, sediment-free water for optimal growth. The proximity of different climate regimes gives Hawai‘i a highly diverse set of ecosystems. As colonizing organisms move into the numerous different ecological niches, they undergo an **adaptive radiation** of species, resulting in one of the most highly **endemic** and unique groups of organisms on the planet. Rates of soil formation are also dependent on climate. Sufficient weathering is required to break down **parent material**, yet too much weathering will remove nutrients, ultimately rendering soils infertile. Native ecosystems, as well as agricultural systems, function best in conditions of optimal rainfall and soil fertility, yet these parameters can and do change over very short distances.

See Chapter 8: Soils to learn more about the effect of weathering on the soils of Hawai‘i.

Climatic diversity and steep climate gradients make Hawai‘i a unique natural laboratory for basic scientific research and applied agricultural research. The high-altitude, cloud-free summits of Mauna Kea and Mauna Loa are ideal sites for astronomical and atmospheric research, respectively. These same climatic features draw tourists from around the world and influence the development of human communities in the islands. Not surprisingly, most development occurs on the sunny leeward sides of the islands, but, unfortunately, most water resources are found on the windward sides. This paradox is both a problem and an opportunity for **sustainable** resource management, both now and in the future.

Climate Change

Hawai‘i's steep climate gradients also provide a unique opportunity to study the effects of **climate change**. When global temperatures rise or fall, Hawai‘i's ecosystems migrate up or down the mountainsides. This phenomenon can be observed for past climates through the analyses of fossil pollen grains. During glacial epochs, the summits of Mauna Kea, Mauna Loa, and Haleakalā were covered by ice caps. Clear evidence of glaciation is seen on the slopes of Mauna Kea today, where terminal **moraines** mark the maximum extent of ice, 18,000 years ago. Additionally, ancient **sand** dunes—now **lithified** to calcareous **sandstone**—mark the position of sea level highstands during **interglacial** periods.

Climate scientists have long identified the summits of Hawaiian volcanoes as ideal sites for atmospheric study. In 1956, NOAA established the Mauna Loa Observatory (MLO) at an elevation of 3500 meters (11,500 feet) on the north flank of Mauna Loa. MLO is well above the trade wind inversion, and it is located more than 3200 kilometers (2000 miles) from any continental landmass. Instrumentation at MLO therefore samples very clean air in the upper atmosphere, and MLO is the oldest and most important baseline station for analysis of atmospheric composition.

Atmospheric carbon dioxide is among the many parameters measured at MLO. The CO_2 record extends from 1958 to present, and it shows the influence of both natural and **anthropogenic** processes (*Figure 9.19*). 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, while CO_2 accumulates in the atmosphere during

Hawai‘i

sand • *rock material in the form of loose, rounded, or angular grains, and formed as a result of the weathering and decomposition of rocks.*

lithification • *the process of creating sedimentary rock through the compaction or sementation of soft sediment.*

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

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

anthropogenic • *caused or created by human activity.*

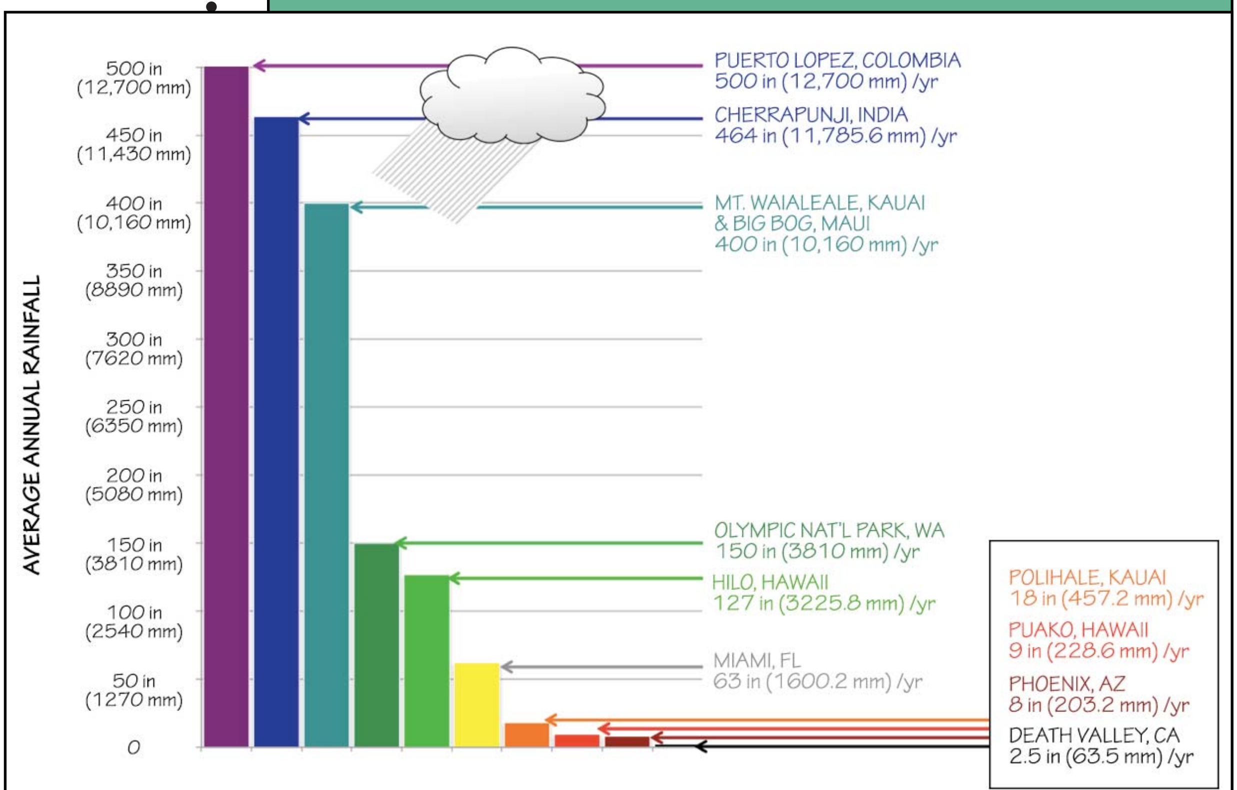
9

Climate

Hawai‘i

Rainfall Extremes

Two locations in Hawai‘i—Mt. Wai‘ale‘ale on Kaua‘i and the more recently monitored Big Bog on Haleakalā, Maui—average 1029 cm (405 inches) of annual rainfall. Many areas on the islands’ leeward coasts receive less than 50 cm (20 inches) of annual rainfall. The village of Puakō on Hawai‘i’s *kona* coast averages 23 cm (9 inches) per year and is the driest inhabited spot in the islands, while the summit of Mauna Kea receives only 20 centimeters (8 inches) per year—the driest place in the state, with the same rainfall as Phoenix, Arizona.



(See TFG website for full-color version.)

The truly remarkable aspect of this large variation in rainfall is the short distance that separates rainy and dry areas in Hawai‘i. The wettest (Big Bog) and driest (Mauna Kea) places in Hawai‘i are only 121 kilometers (75 miles) apart. On the continental US, Olympic National Park in

Washington is the rainiest spot (380 centimeters [150 inches] per year) while Death Valley, California, is the driest (6.4 centimeters [2.5 inches] per year). This variation in rainfall is not nearly as large as that measured in Hawai‘i, and the two locations are 1450 kilometers (900 miles) apart.

Globally, the rainiest places on Earth are on the windward slopes of the world's largest mountain ranges. Puerto Lopez de Micay, Colombia, is in the Andean foothills, while Cherrapunji, India, receives orographic rainfall from moist air flowing during the monsoon season from the Indian Ocean to the Himalayas. Cherrapunji has only recently had its title as the "Rainiest Spot on Earth" washed away by Puerto Lopez, but it still holds the record for most rainfall in a single year: 2647 centimeters (1042 inches) in 1961.

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

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 CO_2 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 MLO data from Hawai‘i are our oldest and most reliable direct measurements of anthropogenic atmospheric change.

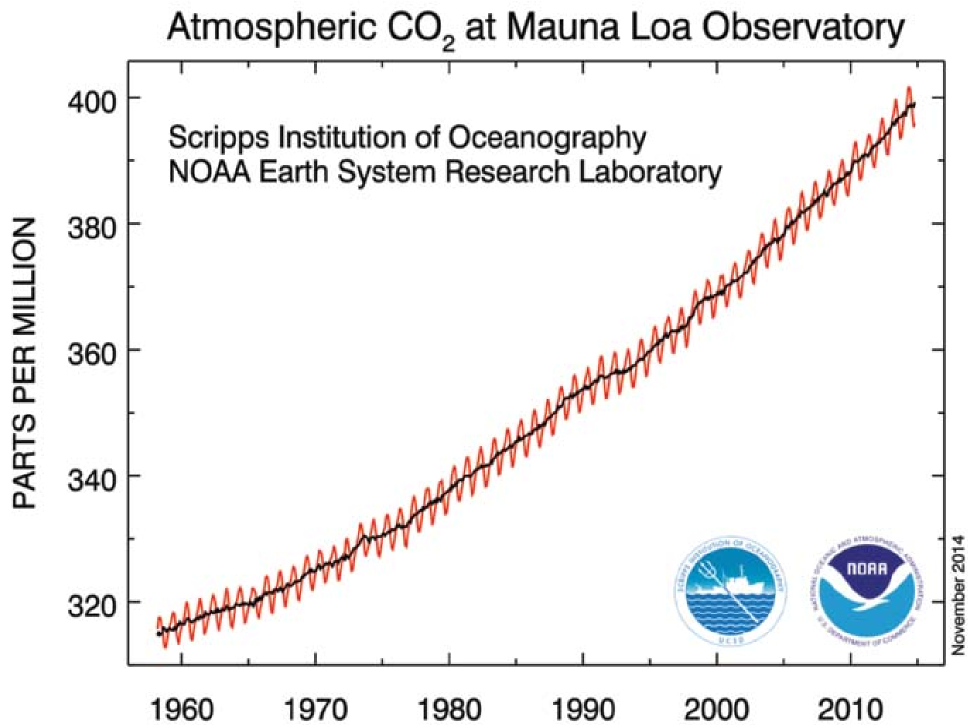


Figure 9.19: Measured concentration of atmospheric carbon dioxide (1958 to present) at MLO.

Future Climate of the West

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 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 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.

See Chapter 6: Glaciers for more about interglacial periods.

Future

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

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.*

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. The burning of fossil fuels and removal of forests are the main human activities that alter the composition of the atmosphere. Most dramatically, we are adding huge amounts of carbon dioxide and other greenhouse gases, which trap heat radiated by the Earth. Since plants remove CO_2 from the atmosphere, deforestation compounds the issue.

It is extremely difficult to predict the outcome of putting increasing amounts of carbon (as CO_2) into the atmosphere, but there are several important reinforcing effects already being observed. 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, the carbon in the soils will become 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 linger in the atmosphere for years.

The West contributes significantly to climate change. The population of any industrialized and particularly wealthy country produces pollution. The more than 54 million residents of the West 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 Western states, California emits by far the most greenhouse gases. In 2011 California was the second highest greenhouse gas emitter in the nation, behind only Texas, and the majority of its emissions came from transportation.

On the other hand, Western states are making changes to reduce human impact on the climate. The city of Seattle was an early adopter of 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, Washington, California, and Oregon are the top three producers of **renewable** electric energy in the nation.

hectare *• a metric unit of area defined as 10,000 square meters.*

Trends and Predictions

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

- Temperatures in the West have increased in the last 25 years during all seasons.
- Nighttime temperatures in the Southwest have increased by almost 1.7°C (3°F) since 1900.
- The average annual number of wildfires of over 400 **hectares** (1000 acres) has doubled in California since the 1970s.
- The freeze-free season in the Northwest is on average 11 days longer for the period of 1991–2010, compared with that of 1961–1990.
- Heavy downpours have increased by 18% in the Northwest from 1948 to 2006.
- Statewide average temperatures in Alaska have increased, with winter temperatures increasing the most: up 3.2°C (5.8°F) from 1949 to 2011.

Climate models predict that the West's climate will continue to warm, and that the average annual temperature will rise by 2° to 6°C (3° to 10°F) by the end of the 21st century. In Alaska, temperatures are expected to rise more rapidly, by 2° to 4°C (3.5° to 7°F) by the *middle* of the 21st century. These increased temperatures lead to a whole host of other effects, including drier soils from more evaporation, the increased likelihood of drought and fires, and more rain (rather than snow) in the winter.

Water supply is a critical issue in the West, and communities will need to adapt to changes in precipitation, snowmelt, and runoff as the climate changes. Models predict that winter and spring storms in Nevada will shift northward, dropping less rain and snow in already arid areas. California will likely be faced with less water flowing in its rivers, declining high elevation forests, and expanding grasslands, along with increased pressure on the water supply for agriculture and cities (*Figure 9.20*).

The Northwest is expected to see less summer precipitation and more winter precipitation, and more of the winter precipitation falling as rain rather than snow. Over the past 40 to 70 years, the Cascade Range has experienced a 25% decline in snowpack measured on April 1, a trend that is expected to continue. This means less water from snowmelt in the warm season. Spring runoff in Northwestern streams is expected to occur nearly 20 to 40 days earlier during the 21st century. Sea level rise from melting glaciers and the thermal expansion of a warmer ocean will be a concern for cities such as Seattle, Tacoma, and Olympia (*Figure 9.21*).

Figure 9.20: This lake near San Luis Obispo, California contains barely any water following a several-year drought.

Climate models project that Alaska will receive more precipitation, but that soils will actually become drier due to increased evaporation from warmer air temperatures. Summers are expected to support a longer growing season, and also to see more drought and wildfires. Invasive insects that damage Alaskan trees will be better able to survive warmer winters, and will therefore increase and spread. Sea ice will cover the ocean for shorter portions of the year, possibly changing the distribution of plankton blooms, a part of the marine food chain upon which Alaska's fisheries depend.

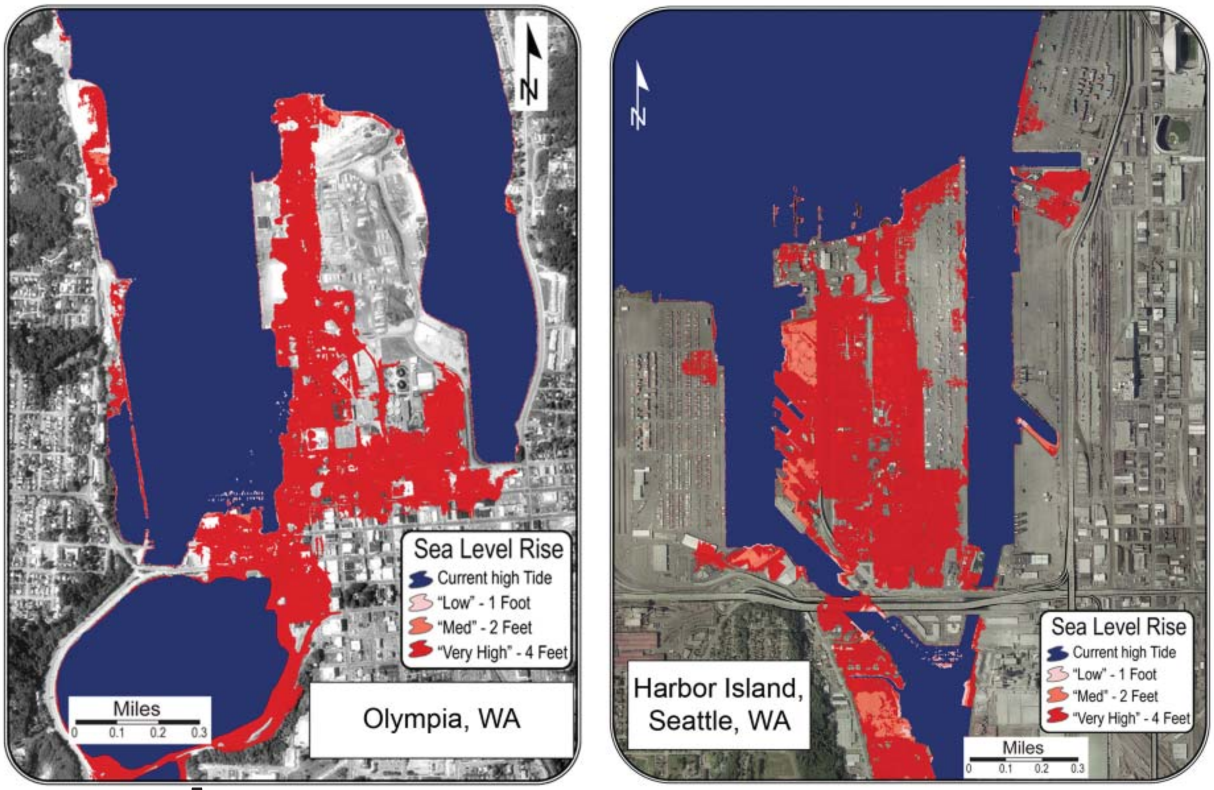


Figure 9.21: Maps showing portions of the cities of Olympia and Seattle, Washingrton that will be inundated if sea level rises by one, two, or four feet. (See TFG website for full-color version.)

Hawai'i stands to be significantly impacted by climate change, with serious potential effects on both its ecosystems and economy. Rising temperatures could disrupt the pattern of trade winds, changing rainfall patterns across the islands and creating periods of flooding or drought. Higher temperatures will also place more stress on native plants and animals, enabling the proliferation of invasive species that are better able to withstand temperature extremes. Warming oceans and increased ocean acidity could trigger massive coral die-offs as well as affecting ocean circulation. Finally, sea level rise could inundate much of Hawai'i's coastline—the worst case scenario of a 2-meter (6-foot) sea level rise would bring Hawai'i's coast 1.6 kilometers (1 mile) inland in some places, submerging or eroding important economic locations like Waikiki Beach and parts of Honolulu.

Resources

Books

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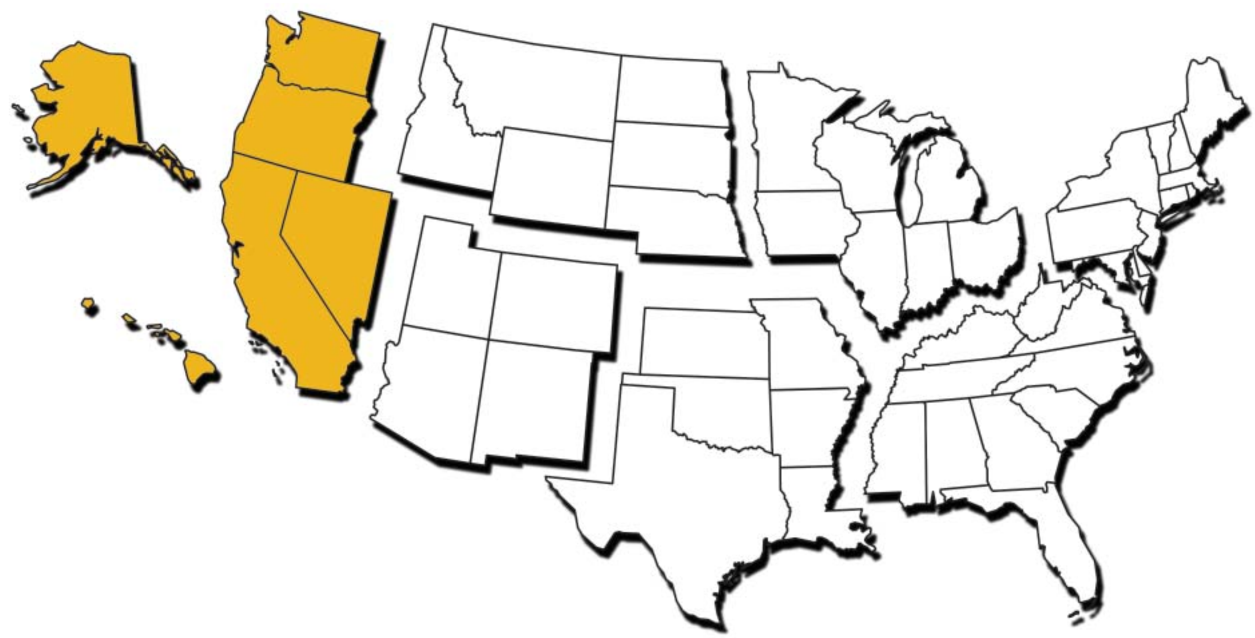
Western Regional Climate Center, http://www.wrcc.dri.edu/. (A wide variety of weather and climate data and state-by-state climate narratives.)

The *Teacher-Friendly* Guide™

to the Earth Science of the Western US



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