GREATER YELLOWSTONE CLIMATE ASSESSMENT

Past, Present, and Future Climate Change in Greater Yellowstone Watersheds
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Steven Hostetler ¹, Cathy Whitlock ², Bryan Shuman ³,
David Liefert ⁴, Charles Wolf Drimal ⁵, and Scott Bischke ⁶

¹ Co-lead; Research Hydrologist; US Geological Survey Northern Rocky Mountain Science Center, Bozeman MT

² Co-lead; Regents Professor Emerita of Earth Sciences, Montana Institute on Ecosystems, Montana State University, Bozeman MT

³ Wyoming Excellence Chair in Geology & Geophysics, University of Wyoming, Laramie WY; Director, University of Wyoming-National Park Service Research Center at the AMK Ranch, Grand Teton National Park

⁴ Water Resources Specialist, Midpeninsula Regional Open Space District, Los Altos CA; PhD graduate, Department of Geology and Geophysics, University of Wyoming, Laramie WY

⁵ Waters Conservation Coordinator, Greater Yellowstone Coalition, Bozeman MT

⁶ Science Writer, MountainWorks Inc., Bozeman MT
Land Acknowledgment
The lands and waters of the Greater Yellowstone Ecosystem have been home to Indigenous people for over 10,000 years. In the most recent millennium, over a dozen Tribes have considered this region a part of their traditional (ancestral) homelands. This includes, but is not limited to, several Tribes and bands of Shoshone, Apsáalooke/Crow, Arapaho, Cheyenne and Ute Nations, as well as the Bannock, Gros Ventre, Kootenai, Lakota, Lemhi, Little Shell, Nakoda, Nez Perce, Niitsitapi/Blackfeet, Pend d’Oreille, and Salish. We pay respect to them and to other Indigenous peoples with strong cultural, spiritual, and contemporary ties to this land. We are indebted to their stewardship. We recognize and support Indigenous individuals and communities who live here now, and those with cultural and spiritual connections to these Homelands.

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Greater Yellowstone Climate Assessment: Past, Present, and Future Climate Change in Greater Yellowstone Watersheds is available in digital format at www.gyclimate.org. While included in this report, a stand-alone Executive Summary is also available.

Suggested citation
2. CLIMATE, CLIMATE VARIABILITY, AND CLIMATE CHANGE IN THE GREATER YELLOWSTONE AREA

Cathy Whitlock, Steven Hostetler, Gregory Pederson, and David Liefert

**Key Messages**

- The climate history of the Greater Yellowstone Area shows changes on timescales ranging from seasons to millennia. Over thousands of years, the primary drivers of natural climate change are cyclical variations in solar radiation related to Earth’s orbit around the sun and associated changes in the amount of greenhouse gas in the atmosphere. Over years to centuries, the natural drivers of climate variability are volcanic activity, solar output, and coupled atmosphere-ocean circulation patterns. [**high agreement, robust evidence**]

- The geologic record of the GYA indicates that the last glaciation (approximately 22,000-13,000 yr ago) was as much as 5-7°F (2.8-3.9°C) colder than the pre-industrial period (1850-1900). Two warm periods in the past are the early Holocene (11,500-7000 yr ago), which was about 1.8-3.6°F (1-2°C) warmer in summer than the pre-industrial period, and the Medieval Climate Anomaly (from 800 to 1300), characterized by prolonged droughts and slightly warmer summers than pre-industrial time. [**high agreement, robust evidence**]

- The average temperature of the last two decades (2001-2020) is probably as high or higher than any period in the last 20,000 yr, and likely higher than previous glacial and interglacial periods in the last 800,000 yr. The current level of carbon dioxide in the atmosphere is the highest in the last 3.3 million years. [**medium agreement, medium evidence**]
**WHAT IS CLIMATE?**

*Climate* differs from *weather*. Weather refers to atmospheric changes that occur over minutes to months and are reflected, for example, by the temperature, humidity, and precipitation at a location and particular time. Climate is the long-term average of weather over an extended time period, such as decades to centuries. In this report, we define the climate base period for comparison with future periods as the 1986 through 2005 average or mean. We chose this 20-year base period because 1) it captures observed global warming trends and, therefore, is a conservative (warm) baseline; and 2) climate model simulations of the historical period end in 2005 and projections of future climate in this Assessment begin in 2006.

The *climate system* describes all the interacting components that create Earth’s climate: the atmosphere (air), hydrosphere (water), the cryosphere (ice and permafrost), lithosphere (Earth’s upper rocky layer), and biosphere (living things). Climate change refers to shifts (e.g., decadal and longer) in the average or mean climate, which can be abrupt or gradual, as evidenced in historical and geological records discussed later in this chapter and in Chapter 3. A climate trend is a long-term trajectory of change in the mean climate. Climate variability refers to short-term departures from the mean state of the climate (note that climate variations are longer than individual weather events, spanning seasons or years). In the coming decades, climate change is projected to trend toward ever warmer conditions; however, as illustrated in Figure 2-1, climate variability may result in seasons and years that are warmer or colder than the 20-year means, just as occurs today.

![Figure 2-1. An example of climate change that displays both trend and variability. The black line shows steadily increasing temperature through time with year-to-year temperature variations along with a linear trend shown by the gray line. The three horizontal lines indicate the average or mean temperature for three 20-year periods, as examples of the averaging periods used in the Assessment, and the shading shows the range of temperature variability (minimum to maximum) during each averaging period.](image-url)
CLIMATE AND WATER VARIABLES DISCUSSED IN THE ASSESSMENT

The international climate science community uses over 50 essential physical, chemical, and biological variables to characterize the state of the Earth’s climate (WMOa undated). To qualify as an essential climate variable, the information about it must be 1) worldwide in coverage; 2) freely available; 3) quality controlled with appropriate documentation; and 4) considered relevant by an international panel of climate experts. Our report focuses on a small subset of the 50 essential climate variables that are relevant to the GYA:

- **Air temperature** (referred to *temperature* in this report) is a measure of how hot or cold the air is with reference to some standard value. Seasonal variations in temperature result from latitudinal differences in the amount of solar radiation received at the Earth’s surface, contrasts in seasonal heating of land and oceans, and atmospheric circulation.

- **Precipitation** is the quantity of water (liquid or solid) falling to the Earth’s surface at a specific place over a given period. Like temperature, precipitation varies from season to season and place to place and depends on coupled atmospheric-ocean circulation.

In addition to the climate variables, we also focus on other variables:

- **Snowfall** and **snowpack** are measures of the amount and fate of solid winter precipitation. Snowfall is the amount of accumulated snow after a storm. It is measured in terms of the depth of solid water it contains. In mountainous and relatively dry areas like the GYA, 10 inches (25 cm) or more of snow is often needed to create 1 inch (2.5 cm) of liquid water when melted. Snowpack is the amount of snowfall that accumulates over the cold season. It also is measured by both depth (snow depth) and the amount of liquid water it stores (called snow water equivalent or SWE).

- **Streamflow** (also called *discharge*) refers to water moving within a river measured by the volume of water passing a point in a given time. Streamflow is measured at gaging stations in units of cubic feet per second or cubic meters per second. In GYA, streamflow is strongly controlled by the seasonality of runoff from snowmelt.

- **Runoff** is the depth of water uniformly distributed over an area, such as a watershed. It is the potential amount of water available for groundwater and streamflow.

- **Evapotranspiration** is water lost through evaporation from bare soil and transpiration by plants. **Potential evapotranspiration** is the amount of evapotranspiration that would occur under unlimited water availability.

- **Drought** is a prolonged period of dryness relative to long-term average conditions. The climatological community defines four types of drought: 1) **meteorological drought** occurs when unusually dry weather patterns persist over an area from days to months; 2) **hydrological drought** refers to low-water supply and usually occurs after many months of meteorological drought; 3) **agricultural drought** occurs when
low soil moisture limits survival and production of crops and grazing lands; and 4) socioeconomic drought reflects the economic and social impact of a combination of hydrological and agricultural drought. In this report, we use the term drought, without distinguishing the type, but unless otherwise noted, we are referring to meteorological or hydrological drought.

- **Palmer Drought Severity Index (PDSI)** is a standard measure of drought that combines temperature or potential evapotranspiration and precipitation data to quantify dryness or wetness relative to average or normal conditions. The PDSI describes soil moisture conditions (generally the top meter of soil).

- **Vapor pressure deficit** is a measure of the drying capacity of the atmosphere based on air temperature and relative humidity. High vapor pressure deficits (i.e., high temperature combined with low humidity) can limit tree growth, increase their vulnerability to drought, and dry fuels, all potential contributors to wildfire.

**Present Climate**

The climate of the GYA is characterized by long, often bitterly cold winters. Summers are short and mild. May and June are generally the wettest months in the valleys; August is generally the driest. Snow is the primary form of winter precipitation.

The GYA’s climate is attributed primarily to its mid-latitude continental location, high average elevation, and distance from the Pacific and Gulf coasts. At approximately 44°N latitude, the region has long summer days and long winter nights. Even summer days are relatively cool, however, due to the high elevation of the GYA. GYA receives air masses not only from the Pacific Ocean to the west, but also from the Arctic Ocean to the north and Gulf of Mexico to the south. The relative contribution of these air masses and the moisture they entrain is reflected in seasonal temperature and precipitation patterns for any given year (Whitlock and Bartlein 1993).

Precipitation generally increases with elevation in GYA, as it does throughout the West. Cold, wet winters in the GYA reflect a combination of moisture carried by storms off the Pacific Ocean and frequent, cold Arctic air mass intrusions. Most of these storms are funneled northeastward along the Snake River Plain and the precipitation they carry is delivered as snow over the high mountains and plateaus of the GYA (Farnes 1997). Cold, dry weather in winter occurs when a sustained southward incursion of an Arctic air mass brings subzero temperatures (Fahrenheit) to the region. Winters are generally wetter in the Teton Range and western Yellowstone Plateau region than in the eastern GYA. Pacific storm systems, as well as moisture transported along the Rocky Mountain Front from the Gulf of Mexico, account for wet spring conditions in the region.

Summers in much of the GYA are typified by warm, dry conditions punctuated by thunderstorms. During summer, Pacific storm tracks shift well north of the GYA so summer rainfall is delivered by low-pressure centers and their related atmospheric disturbances (or fronts). Moisture in the northern and eastern GYA originates from the subtropical Gulf of Mexico, whereas that in the southwestern GYA comes from the subtropical Pacific Ocean.
Year-to-year and decadal climate variations that affect the GYA derive from recurring, global scale changes in atmosphere and ocean circulation patterns. The El Niño-Southern Oscillation (ENSO), for example, is a climate pattern set up by changes in sea-surface temperature and atmospheric pressure in the equatorial Pacific Ocean that can persist for several years. Warmer-than-normal equatorial ocean surface temperatures are associated with El Niño events, whereas colder surface temperatures are associated with La Niña events. ENSO influences storm tracks and pressure systems at mid-latitudes through atmospheric connections (called teleconnections) that, in turn, influence surface climate conditions across the West, including the GYA (Figure 2-2). The Pacific Decadal Oscillation (PDO) is a similar, multi-year pattern of climate variability forced by sea-surface temperature changes that occur on decadal scales. Phases of the PDO are identified by warm or cold ocean temperature patterns in the north Pacific Ocean. Even persistent decades of warmer and colder than normal sea surface temperature in the North Atlantic Ocean known as the Atlantic Multi-decadal Oscillation (AMO) can interact with ENSO and PDO to affect long-term drought in the GYA (McCabe et al. 2004, 2008).

![Temperature and precipitation patterns during El Niño and La Niña events from 1950-2010](image)

Figure 2-2. Differences or anomalies from mean annual temperature (top row) and precipitation (bottom row) from 1950-2010 during El Niño (left column) and La Niña (right column) (figure from Kennedy 2012). El Niño events tend to bring warmer and drier conditions than average to the Greater Yellowstone Area (GYA), whereas La Niña events tend to bring cooler and wetter conditions, especially in the western GYA. El Niño-Southern Oscillation (ENSO) patterns are unstable spatially and through time as a result of interactions with other atmosphere-ocean processes. A particular ENSO event does not always result in the same surface climate conditions in the GYA.
ENSO and PDO patterns alter the north-south position of Pacific storm tracks across western North America, which can result in large and contrasting variations in winter precipitation and air temperature that persist for short (~12-18 months) to long (decades) periods. The regional effects on precipitation from changes in the PDO are strongest along the Pacific Coast in the Pacific Northwest, whereas the greatest influence of ENSO is over the American Southwest and Southeast. On average, El Niño events bring warmer and drier conditions to the GYA whereas La Niña events bring cooler and wetter conditions; however, interaction with other atmosphere-ocean circulation processes often affect this generalized pattern. Thus, not all ENSO or PDO events have a similar effect on the climate of the GYA (Pederson et al. 2011a,b; Abatzoglou 2011; Pederson et al. 2013).

**Past Climate Change**

Natural climate change, ever ongoing, can be examined on many timescales. Over millions to 100s of millions of years, changes in the size and position of continents and ocean basins and related mountain uplift have shaped the Earth’s climate. Over tens to hundreds of thousands of years, repeated cycles of cold (called glacial periods or ice ages) and warmth (called interglacial periods) have been caused by seasonal and latitudinal variations in the amount of solar radiation received by the Earth.

Glacial-interglacial cycles result from continual changes in the tilt and wobble of Earth’s axis and in the elliptical orbit of the Earth around the sun. These recurring astronomical drivers1 of climate change, known as Milankovitch cycles, are the pacemaker of the ice ages (Ruddiman 2013). Levels of greenhouse gases in the atmosphere also varied with these cycles, amplifying the warmth of interglacial periods and the cold conditions of glacial intervals. The last ice age on the planet occurred between about 115,000 and 11,700 yr ago, with maximum glaciation between 27,000 and 19,000 yr ago in different regions (Clark et al. 2009). Global warming of 5-7°F (3-4°C) occurred between 19,000-11,000 yr ago, ushering in the current interglacial period, which is called the Holocene (the last 11,700 yr) (Clark et al. 2012; IPCC 2013).

Climate variations on timescales of centuries or less tend to be more regional in scale, but with different principal drivers (Ruddiman 2013):

- Over decades to centuries, volcanic activity, changes in solar output, and global-scale changes in atmosphere-ocean circulation patterns have caused climate to vary. Notable examples of such variations have resulted in climate anomalies relative to a defined average, such as the persistent cold conditions and widespread glacial advances that occurred from about 1600-1850, known as the Little Ice Age, and the periods of warmth and drought that define the Medieval Climate Anomaly from about 800-1300.

- Over interannual to decadal timescales, persistent atmosphere-ocean circulation patterns, such as ENSO and the PDO, are the important drivers of climate variations (discussed above).

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1 Some authors use the word *forcings* instead of *drivers*. For this report we will generally use the latter.
The last 20,000 years

The climate of the GYA has varied widely over the last 20,000 yr—from the culmination of an ice age to periods that were warmer than the pre-industrial period\(^2\). The climate history of the GYA, as interpreted from the geologic record and measured by observations, provides a useful context for perspective on the significance of current and projected climate changes.

GYA was extensively covered by ice during past glacial periods. Ice cover during the recent Pinedale glaciation (22,000-13,000 yr ago) and the previous Bull Lake glaciation (150,000-140,000 yr ago) are shown in Figure 2-3 (Licciardi and Pierce 2018). The Pinedale glaciation began when glaciers started to grow and expand in the Beartooth-Absaroka Mountains of northeastern GYA and Gallatin Range of northwestern GYA. By 15,000 yr ago, individual glaciers from the two regions had coalesced into a large Yellowstone ice cap centered over present-day Yellowstone Lake. Valley glaciers flowed from the ice cap down all the major river valleys. Geologists name the terminal ridges of gravel and boulders (moraines) deposited by these valley glaciers by their location (e.g., the Chico moraine, the Outer Jenny Lake moraine) and determine the age of the moraines using cosmogenic nuclide dating methods\(^3\). From this information, geologists have determined that the Yellowstone ice cap was asymmetrical; its maximum growth occurred to the southwest, indicative of the dominant source of precipitation from the direction of the Snake River Plain (Licciardi and Pierce 2018). Glaciers started to recede first in the northeast in the Clarks Fork drainage 19,800 yr ago, and last in the south at Jackson Lake 15,500 yr ago. Glacial ice was largely gone from the GYA by 12,000 yr ago.

\(^2\) Pre-industrial refers to the period when fossil-fuel burning had yet to change the climate. This period (1850-1900) is used as baseline for assessing current climate change (IPCC 2018).

\(^3\) Cosmogenic nuclide dating uses the interactions between cosmic rays and the atomic nuclides found in glacially transported boulders to provide age estimates for the rock’s exposure at the Earth’s surface (Davies 2020). In other words, cosmogenic nuclide dating determines how long the boulders in moraines have been at the surface, which in turn provides the age of glacier position.

![Yellowstone Lake was once covered by an ice cap](Photo courtesy of Cathy Whitlock)
Figure 2-3. Extent of ice cover during the Pinedale (22,000-13,000 yr ago) and previous Bull Lake glaciations in the Greater Yellowstone Area (GYA) (image from Licciardi and Pierce [2018]; reprinted with permission). Pinedale-age glaciers were larger than those of Bull Lake in the northern and eastern parts of GYA, and smaller in the southern and western parts. Ages, shown in thousands of years ago (kiloannum = ka), of the glacier limits are based on cosmogenic exposure dating of moraine boulders. Contours (purple lines) show the elevation of the ice cap surface in thousands of feet. The three circles provide ages (ka) and locations of the highest ice elevation at 15,000, 18,000, and 20,000 yr ago. Note the southwesterly advance of the ice cap with time.
The present-day landscape, river systems, and lakes of the GYA were formed largely during the Pinedale glaciation by the erosional and depositional processes associated with ice advance, melting, and recession (Good and Pierce 1996). The ruggedness of Teton and Wind River ranges exemplify glacial sculpting under former ice divides (Figure 2-4). The sagebrush-covered terraces within the major river valleys were created by high-volume braided rivers that flowed from melting glaciers and deposited coarse gravels beyond the ice margins. These porous gravels are the source of shallow, groundwater storage in most of the GYA’s river basins. Many lakes in the GYA (e.g., Jenny Lake, Jackson Lake, Fremont Lake) are dammed by moraines of gravel that were deposited at the terminus of valley glaciers. Other smaller lakes (e.g., Blacktail Pond, Swan Lake, Swamp Lake) were formed when blocks of ice buried under glacial debris melted with warming temperatures and created a depression on the land surface.

Figure 2-4. This iconic photo by Ansel Adams shows the legacy of past glaciation in Grand Teton National Park (1942). About 16,000 yr ago, the southern margin of the Yellowstone ice cap reached the valley of Jackson Hole. As the climate warmed about 15,500 yr ago, the position of the southern ice margin retreated northward (to the right in the photo). In the process of ice melting, an ancient, braided Snake River flowed from the glacial terminus and deposited a sheet of gravel and cobbles on the valley floor. These gravel deposits formed flat terraces that are today covered by sagebrush (middle distance). The Snake River continues to carve through these glacial deposits in a meandering pattern, creating gravel bars covered with cottonwoods (foreground). The Teton Range (background) was carved by their own set of glaciers; the small glaciers in the Teton Range today are remnants of more extensive ice cover. (Photo credit: US National Archives Identifier 519905.)
As the climate warmed and glaciers started to melt in the GYA, plants were able to colonize areas that had previously been covered by ice. Pollen buried in the sediment in Yellowstone’s lakes indicates that the first conifer to appear was juniper, probably common juniper (*Juniperus communis*), which established in a relatively open, tundra-like landscape. Next came Engelmann spruce (*Picea engelmannii*), followed by whitebark pine (*Pinus albicaulis*), limber pine (*Pinus flexilis*), and subalpine fir (*Abies lasiocarpa*) (Krause and Whitlock 2017). Lodgepole pine (*Pinus contorta*) was widespread after 11,000 yr ago, and Douglas-fir (*Pseudotsuga menziesii*) was the last conifer to arrive and expand its range after 9000 yr ago (Iglesias et al. 2018).

This sequence of forest development shows the capacity of the region’s conifers to respond to rising temperatures by adjusting their range and abundance over thousands of years. Similar responses will certainly take place in the future, but likely at a faster rate. Some native species (e.g., whitebark pine) may no longer find suitable climate in GYA and become regionally absent (Chang et al. 2014) and different species (e.g., Gambels oak [*Quercus gambelii*], western larch [*Larix occidentalis*], ponderosa pine [*Pinus ponderosa*]) may be better suited to future climate conditions. The rate of current climate change, however, is many times faster than what occurred in the past, and it is doubtful that species will be able to keep pace on a timescale relevant to forest management (Bartlein et al. 1997).

The current interglacial period, the Holocene, began as the latest of a series of interglacial periods. Two warm intervals in the Holocene serve as important benchmarks for evaluating future climate and ecological change in the GYA (Whitlock and Hostetler 2019). The first was a prolonged period from about 11,500 to 7000 yr ago (the early-Holocene period) when summers in the region were on average 1.8-3.6°F (1-2°C) warmer than the pre-industrial average (Kutzbach et al. 1998; Bartlein et al. 1998). The causes of this warming were increased solar radiation during the Northern Hemisphere summer resulting from slow Milankovitch variations in the tilt of the Earth’s axis and rising levels of greenhouse gases in the atmosphere.4

Pollen records indicate that the early-Holocene period in the GYA was a time of expanded lodgepole pine forest and more Douglas-fir and aspen (*Populus tremuloides*) compared to present. The upper tree line lay at a higher elevation than at present in response to longer growing seasons, and lower tree line shifted upslope in response to drought (Whitlock 1993; Iglesias et al. 2018). Many of the small lakes and wetlands in northern Yellowstone National Park dried during the early Holocene, and fires were more frequent. Snow and ice fields at high elevations shrank in size and accumulated plant debris and artifacts that were preserved by ice during subsequent cold periods (see box). Longer summers at Yellowstone Lake likely resulted in earlier ice-off in spring and longer open-water conditions in fall (Thompson et al. 1998).

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4 Winter insolation was lower in the early Holocene and as a result winters in the GYA were probably cooler than during pre-industrial time.
Snow and Icefields of the Greater Yellowstone Area

Patches of year-round ice are found at high elevations throughout the Greater Yellowstone Area (GYA), and scientists have discovered that some of these patches are thousands of years old and preserve valuable information about the past. Recent warming has resulted in substantial melting and shrinking of the ice bodies, exposing organic artifacts that have been frozen in the ice. GYA artifacts provide unique insights into the activities of ancient hunter-gatherers in the high mountains. For example, a 10,300-year-old atlatl dart, used in hunting big game, was recovered from a melting ice patch in northwestern Wyoming (photos).

These ice patches are also a valuable source of paleoenvironmental and paleoclimatic information (Chellman et al. 2021). In 2018, a 6-m-long ice core was taken from the same ice patch where the atlatl dart shaft was found. The core contained 29 layers of plant remains (e.g., seeds, pollen, needles, and organic matter), animal dung, and dust (photo). Radiocarbon dating revealed that these debris layers formed during periods of warm and/or dry conditions that occurred on average every 300 yr over the last 10,000 yr.

A nearby melting ice patch uncovered fossil logs of whitebark pine (*Pinus albicaulis*), indicating that during a warm period 5000 yr ago conifers grew at elevations at least 100 m (330 ft) above present-day tree line. Tree-ring analysis of the wood showed that this warm period persisted for about 800 yr. Scientists expect more discoveries as a warming climate continues to melt old ice patches. Uncovered debris and artifacts will help us better understand past high-elevation environments, as well as the people who lived there.

Left: Scientists taking an ice core from a GYA ice patch. 
Right: Sampling logs from ancient whitebark pines that have been exposed from a melting ice patch. 
(Photo credits: Greg Pederson)
The last 1000 years

The second period of warmth since the last ice age, the Medieval Climate Anomaly (800-1300), occurred on most continents, although the underlying cause of warming is not fully understood. Tree-ring records and other studies from GYA offer regional information about past temperature, precipitation, summer drought, snowpack, and streamflow over the last 1000 yr. The Medieval Climate Anomaly was overall not as warm as the early Holocene and instead was characterized by multi-decadal periods of warm summer temperatures, low snowpack, and dry conditions, which are referred to as megadroughts (Pederson et al. 2011b; Martin et al. 2019; Heeter et al. 2021).

Megadroughts occurred in the GYA and across much of the western United States in the early 600s, late 800s, 1200s, and late 1500s (Williams et al. 2020). These dry periods led to more fires, desiccation of small lakes, reduced streamflow, an upslope shift in upper tree line, and reduced Old Faithful geyser activity (see box) (Meyer et al. 1995; Millspaugh et al. 2004; Pederson et al. 2011b; Hurwitz et al. 2020).

Severe 13th-century Drought Silences Old Faithful

Old Faithful Geyser got its name in the 19th century because its eruptions were both regular and predictable. Recent years of low precipitation have resulted in less frequent eruptions of Old Faithful, and this slowdown has raised concerns from the public.

To investigate this change in eruption frequency, a team of scientists were given permission by Yellowstone National Park to collect 13 mineralized specimens of lodgepole pine (Pinus contorta) wood from the Old Faithful geyser mound (Hurwitz et al. 2020). The fact that trees at one time grew on the mound suggests that the geyser was not actively erupting at some point in the past. When eruptions at Old Faithful resumed, the trees were killed and preserved in mineral deposits. Radiocarbon dating of the wood samples show that tree establishment and associated eruption hiatus occurred in the early-13th through mid-14th centuries (1233-1362).

Independent climate studies based on tree-ring records indicate a severe and sustained drought across GYA in the mid-13th century at the time the trees grew on the Old Faithful mound. The scientists hypothesize that reduced precipitation limited the subsurface supply of water to the geyser basin causing a cessation in eruptions of Old Faithful for an extended period of time.

Old Faithful Geyser in Upper Geyser Basin, probably taken in 1878. (Photo credit: William Henry Jackson, USGS, public domain)
The Medieval Climate Anomaly was followed by a period of above-average snowpack, renewed glacial activity, and cool conditions called the Little Ice Age. The Little Ice Age occurred at different times around the world, and its beginning and end are variously defined (Mann 2003; Neukom et al. 2019). In this Assessment we use the period from about 1550-1850, but note that cooling events began as early as 1300 in the GYA (Heeter et al. 2021). Cooling during the Little Ice Age may have been triggered by heightened volcanic activity, decreased solar activity, a shift in atmosphere-ocean circulation patterns, or even increased forest cover (acting as a carbon sink) during times of human population decline (Mann 2003; Ruddiman 2013). Glaciers at high elevations in the Rocky Mountains were reactivated during this period (Carrara et al. 1987; Menounos et al. 2009), and annual snowpack was high in the GYA during the years of 1535-1550, 1600-1620, 1660-1790, and 1845-1895 (Pederson et al. 2011b). Following the Little Ice Age, the lowest snowpack of the last 1000 yr occurred from 1900 to 1949 and since the 1980s (see box).

Changing Snowpack in the Greater Yellowstone Area

The steady decline in snowpack since the 1980s (measured as the amount of liquid water [or snow water equivalent] on April 1) is a concern for natural resource managers and communities that depend on mountain snowpack for their water supply.

While the great ecological and societal importance of mountain snowpack is clear, the observational record of mountain snowpack variability is short. Thus, scientists used records of tree growth that are sensitive to changes in snowpack across the GYA to reconstruct April 1 snow water equivalent for over the past 800 yr (Pederson et al. 2011b).

The reconstruction (see figure) shows a significant decrease in snowpack during the 20th and early 21st centuries as compared to the previous 800 yr. During the Little Ice Age (circa 1550-1850; shown in blue shading), glaciers in GYA, like elsewhere in the northern Rocky Mountains, reached their greatest extent of the Holocene as a result of persistent above average snowpack and cool summers. Conversely, exceptionally low snowpack during the 1930s Dust Bowl drought (shown in red shading) and since the 1980s—both attributed in part to warm summer conditions—has not been observed since at least the Medieval Climate Anomaly (800-1300).

The tree-ring based reconstructions of snowpack in the GYA indicate that variations in summer temperature govern the overall amount of snowpack that persists over the long term (decades to centuries), whereas short-term differences (year-to-year to decadal) in snowpack are caused by variability in precipitation. The snowpack reconstruction implies that the recent decades of extremely low April 1 snow water equivalent relative to the last 800 yr are associated with regional warming; warming in the future will likely continue this trend (as discussed in Chapter 6).
The last 120 years

Observations over the last 120 yr (1900 to present) show long-term trends in temperature and precipitation with substantial year-to-year and decadal variability, including extreme dry and wet episodes relative to average conditions (Figure 2-5C). Some notable events in the GYA associated with trends and variability over the last 120 yr include:

- **Trends across the 120-year period.**—Mean annual temperature and precipitation in the GYA have varied over the last 120 yr with a substantial range of year-to-year variability and extended periods that were drier or wetter and colder or warmer than average (Figures 2-5A and B). After an extended dry period from 1905-1945 that included the 1930s Dust Bowl drought, precipitation has been near or above the long-term average. GYA temperatures were below the long-term average before late 1920s and then increased during the Dust Bowl years. Temperatures then dropped to near average values until the late 1970s, when they started to increase substantially. The combination of changing temperature and precipitation resulted in variable drought conditions as characterized by the Palmer Drought Severity Index (PDSI). The PDSI shows a few extreme droughts in the past 120 yr, such as in the 1930s, 1988, and early 2000s (Figure 2-5C). Extreme cold and heavy snow events that were common in the late 19th century are now rare (see box).

- **Decadal-scale variability: the 1930s Dust Bowl drought.**—Moisture variability across the GYA is evident as wet and dry conditions that lasted for decades (highlighted by 20-year smoothing average in Figure 2-5A and C). The tendency for moisture conditions to persist over extended periods presents unique challenges for resource managers and local communities. For example, sustained low precipitation, elevated temperatures, and drought conditions during the 1930s Dust Bowl event (orange highlighted boxes in Figure 2-5) resulted in years of elevated regional fire activity, severely reduced surface water resources and streamflow, and the foreclosure and sale of many farms and ranches around the GYA (Murphy 2003). In many USGS streamgage records in the GYA, the Dust Bowl drought still ranks as one of the most severe and sustained drought events on record.

The tree-ring based reconstructions of snowpack in the GYA indicate that variations in summer temperature govern the overall amount of snowpack that persists over the long term (decades to centuries), whereas short-term differences (year-to-year to decadal) in snowpack are caused by variability in precipitation.
Year-to-year variability: the 1988 Yellowstone National Park fires.—Unusually little precipitation fell in 1988 (red point, Figure 2-5A), when extensive forest fires swept through Yellowstone National Park. Average temperature was high and precipitation was low in 1988 (Figure 2-5B) resulting in severe drought, as indicated by the Palmer Drought Severity Index (PDSI; Figure 2-5C). PDSI is a measure of drought intensity that accounts for both the current weather and the cumulative effects of precipitation and temperature from previous months. (See the wildfire box in Chapter 3 for more information.)
The Children’s Blizzard of 1888 and Bygone Cold Events
Naomi Schadt, Montana State University, and Cary J Mock, University of South Carolina

A century before the Yellowstone fires of 1988, an extreme natural disturbance of a different type occurred: the Children’s Blizzard of 1888. The morning of January 12, 1888, was warm and calm across GYA and onto the Great Plains, but these conditions abruptly changed as an Arctic cold air mass enveloped the region, causing temperatures to plummet to subzero values. Children were making their normal trek to rural schools, but when the icy weather hit en route, some attempted to return home. Many didn't make it back to their families and perished while stranded in the storm (Potter 2012). It is estimated that 250-500 individuals died in this event (Valle undated).

The Children’s Blizzard of 1888 was one of a series of severe, cold winter storms that swept the United States—from the Rocky Mountains to the East Coast—during the late 1800s and early 1900s. These winter storms were usually preceded by relatively warm weather and characterized by sudden drops in temperature and heavy snow.

Records from Camp Sheridan (now Mammoth) in Yellowstone National Park reported severe cold snaps and heavy snow starting January 3rd and extending to January 20, 1888, the year of the Children’s Blizzard. The lowest temperature recorded was -41°F (-40.5°C) on January 14, 1888. The high temperature on that same day was -25°F (-32°C). During that month, the Camp recorded almost 30 inches (76 cm) of snow. Thirteen out of those 17 snow days experienced lows below -20°F (-29°C) (US National Archives and Records Administration undated).

The previous year, 1887, Montana ranchers experienced high cattle losses in what is now known as “The Great Die-Up.” Heavy snows, low temperatures, and strong winds created a thick crust of ice and snow that livestock could not break through to reach the sparse grasses beneath. Lack of food and exposure to the elements proved disastrous for Montana cattle (LeCain 2017).

Today, subzero cold weather is often associated with cold Arctic air and little snow. National Weather Service data from Bozeman, Montana, and Cody, Jackson, and Mammoth, Wyoming, show periods of extended subzero cold in the last 50 yr, but typically these periods received less than 5 inches (13 cm) of snow. At these four stations, 6 days in the last half century registered temperatures below -40°F (-40°C; the low recorded during the Children’s Blizzard of 1888). All 6 days occurred in Jackson WY (Climate Analyzer undated).

In the last decade (2010-2019), there have been only five times in the GYA when 8 inches (20 cm) or more of snow accumulated in a 48-hour period that also featured subzero drops in temperature. Four of these weather events occurred in Mammoth WY (in 2010, 2014, 2017, and 2019) with the lowest temperature of -29°F (-34°C) during the 2019 storm. The low temperature recorded in Bozeman MT during this same storm was -10°F (-23°C).

No GYA weather event in the last decade measures up to the 7 days of negative temperatures and 30 inches (76 cm) of snow that was recorded between the 3rd and 20th of January 1888. Our winters have gotten warmer and the absence of the extreme, extended sub-zero periods is an indication that the climate of GYA is changing.
CAUSES OF CLIMATE CHANGE

The Earth’s energy balance is driven by solar radiation that is absorbed by land surface and oceans and radiated back to the atmosphere as heat (Figure 2-6). Greenhouse gas (GHG) molecules, like water vapor ($\text{H}_2\text{O}$) and carbon dioxide ($\text{CO}_2$), have chemical bond structures that trap some of the heat from the Earth’s surface that otherwise would escape back to space. In this way, GHGs promote the accumulation of heat in the lower atmosphere that is necessary to sustain life. (Without atmospheric water vapor and GHGs, the global temperature would be -0.4°F [-18°C], roughly 59°F [33°C] colder than present [WMOb undated].)

![Figure 2-6. The greenhouse effect (figure from Le Treut et al. 2007).](image)

The heat-trapping capacity of GHGs has been known since 19th-century laboratory studies: increasing GHG concentrations increases temperature. The ability of a gas to trap heat is determined by the amount of the gas in the atmosphere, how long the gas lasts before breaking down, and the ability of the gas to absorb (or trap) energy. Water vapor is the most abundant GHG in the atmosphere but also one of the fastest to cycle. $\text{CO}_2$ is the second most abundant GHG and has a lifetime of 300-1000 yr (NASAb undated); its concentration recently surpassed 415 parts per million (NOAAc undated). Concentrations of other GHGs in the atmosphere are lower than $\text{CO}_2$, but they have far greater heat-trapping ability. For example, methane ($\text{CH}_4$), which is measured in parts per billion, is 84 times more effective at trapping heat than $\text{CO}_2$ but it only persists in the atmosphere for about a decade (NOAAc undated).
The past changes in climate discussed in this chapter are largely the result of natural drivers that affect the Earth's energy and moisture balances in ways that result in cooling or warming. Additional human-caused or anthropogenic climate drivers—which can reinforce or attenuate the climate response to natural drivers—include changes in land cover, and increasing emissions of greenhouse gases, sulfate aerosols, and particulate matter like ash and soot. Since 1750, human-caused climate drivers have been rapidly increasing and, in the last century, their effect exceeds that of all natural climate drivers combined (see Chapter 4). The primary anthropogenic driver is the burning of fossil fuels, as described in detail in national and international climate assessments (IPCC 2013; USGCRP 2017; Blunden and Arndt 2019). Scientific agreement that humans are the cause of current climate change is overwhelming, as summarized by NASA (NASA undated):

*The vast majority of actively publishing climate scientists—97%—agree that humans are causing global warming and climate change. Most of the leading science organizations around the world have issued public statements expressing this, including international and US science academies, the United Nations Intergovernmental Panel on Climate Change and a whole host of reputable scientific bodies around the world.*

Concentrations of atmospheric CO$_2$ have been directly measured since the 1950s at the Mauna Loa Observatory in Hawaii (Figure 2-7). The concentration exceeded 415 ppm in March 2021, by far the highest level in the past 800,000 yr when natural CO$_2$ levels ranged between 180-290 ppm (EPICA Community Members 2004). The current level of CO$_2$ also implies that today the Earth's climate is warmer than the last 20,000 yr, and likely warmer than previous interglacial and glacial periods in the last 800,000 yr. Recent research based on analysis of Pliocene-age CO$_2$ levels in deep ocean sediment cores suggests that there is more CO$_2$ in the atmosphere than at any time in the past 3.3 million years (de la Vega et al. 2020). GHG levels in the atmosphere will continue to rise unless deliberate action is taken to reverse the trend through mitigation (IPCC 2018).

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SUMMARY

Climate is the long-term average of weather and usually measured over a base period (e.g., 20 yr, from 1986 through 2005, in this report). Climate changes gradually or abruptly lead to different long-term trends and multi-decadal averages. Shorter (e.g., annual or decadal) variability is superimposed on long-term trends. Both trends and variability can change over time, and indeed they are related but should not be confused.

Seasonal temperature and precipitation in the GYA are governed by the relative contribution of air masses from the Pacific Ocean, Arctic Ocean, and Gulf of Mexico regions through the year. Winter and spring precipitation largely comes from Pacific storms, and summer (and sometimes spring) precipitation comes from subtropical sources in the Pacific and Gulf of Mexico. Year-to-year and decadal climate patterns, such as ENSO and PDO, are attributed to large-scale atmosphere-ocean interactions and their influence on surface climate conditions in other regions. Given the inland location of the GYA, the relationship between ENSO and 20th-century climate variability in the GYA is relatively weak.

Figure 2-7. Continuous measurements of atmospheric CO₂ at the Mauna Loa Observatory in Hawaii began in the 1950s. These measurements show the steady rise in CO₂ to the present, as well as the seasonal ups and downs reflecting uptake of CO₂ by the world’s vegetation, most of which is in the Northern Hemisphere (data from Keeling and Keeling 2017).
Climate change has occurred on all timescales in the Greater Yellowstone Area. Gradual changes over thousands of years are largely driven by cyclical variations in solar radiation related to Earth’s orbit around the sun and the natural variability in atmospheric greenhouse gases. Short-term variations occurring over years to centuries are related to changes in volcanic activity, solar output, and atmosphere-ocean circulation patterns.

The high elevations of the Greater Yellowstone area were covered by a large ice field cap from 22,000-13,000 yr ago, with glaciers flowing down all the major valleys to low elevations. The climate was 5-7°F (2.8-3.9°C) colder than the pre-industrial period. Past glaciations were responsible for shaping most of the landforms that we see in the region today.

A period of warming occurred from 11,500-7000 yr ago (the early-Holocene period), when summers were 1.8-3.6°F (1-2°C) warmer than the pre-industrial period. This was a time of vegetation change, drying wetlands, more fires, and shrinking snow fields.

The Medieval Climate Anomaly, from years 800 to 1300, was a time when summers were slightly warmer than the pre-industrial period. This period was characterized by decade-long droughts that brought more fires, lower streamflow, establishment of trees above present tree line, and even a near-century hiatus of geyser activity at Old Faithful. Notable droughts occurred in the early 600s, late 800s, 1200s, and late 1500s. The Medieval Climate Anomaly was followed by cold, snowy conditions in the Little Ice Age from about 1550-1850.

Warming globally and in the GYA over the 20th and 21st centuries is attributed to increased emission of anthropogenic greenhouse gases (e.g., CO₂, CH₄, and others) from the burning of fossil fuels. The average temperature of the last two decades (2001-2020) is probably higher than any period in the last 20,000 yr, and likely higher than previous interglacial or glacial periods in the last 800,000 yr. The current level of carbon dioxide in the atmosphere currently is the highest in the last 3.3 million years.
Literature Cited


