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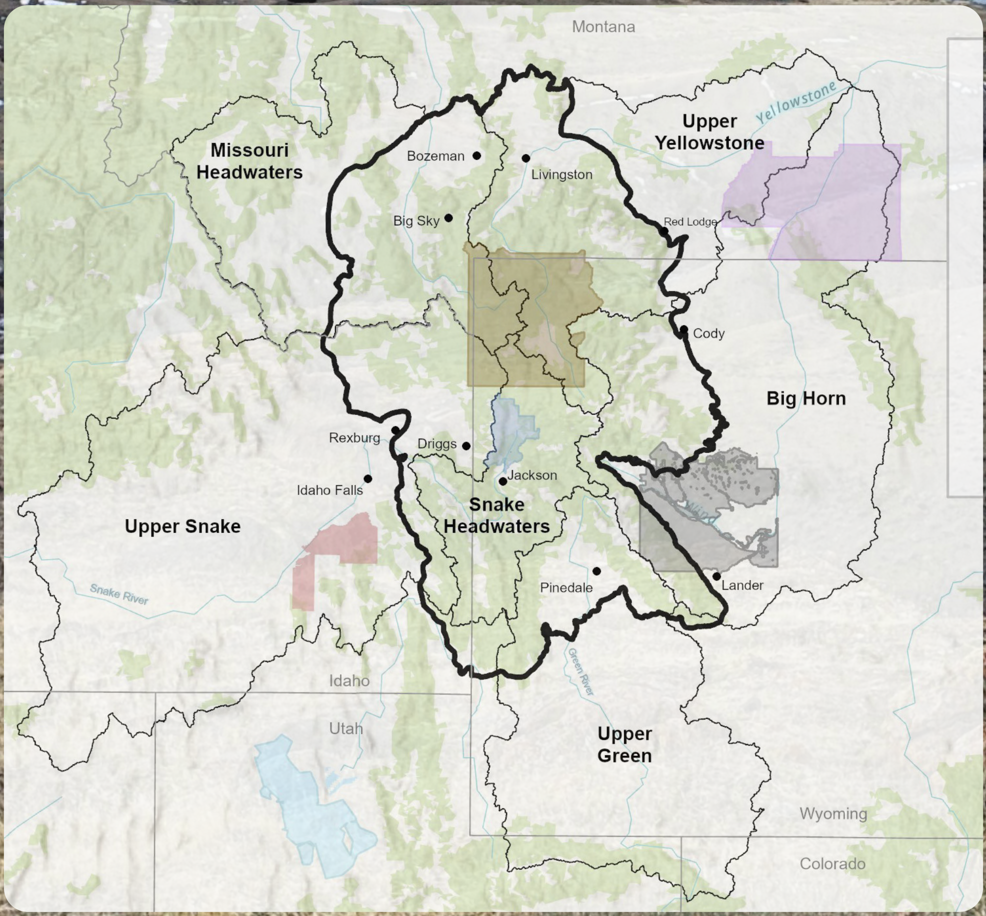
## Executive Summary

# GREATER YELLOWSTONE CLIMATE ASSESSMENT

*Past, Present, and Future Climate Change in Greater Yellowstone Watersheds*

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*first row:* Cody WY (photo credit: US Marine Corp); rail-to-trail conversion between Ashland and Driggs ID

*second row:* pronghorn statues in Pinedale WY; looking west across a portion of Bozeman MT

(photos courtesy of Scott Bischke, except as noted)

**On the cover**

*map:* created by Emily Reed (using ArcGIS® software, copyright ESRI and used herein under license)

*photo:* upper Yellowstone River with Electric Peak in the distance and Gardner MT just visible to the right

(courtesy of Scott Bischke)

# GREATER YELLOWSTONE CLIMATE ASSESSMENT

## *Past, Present, and Future Climate Change in Greater Yellowstone Watersheds*

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Beartooth Mountains, a water source for the Yellowstone River
Photo courtesy of Scott Bischke

**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.

Support for this project came from Montana State University, University of Wyoming, US Geological Survey, Greater Yellowstone Coordinating Committee, and Greater Yellowstone Coalition.

*Greater Yellowstone Climate Assessment: Past, Present, and Future Climate Change in Greater Yellowstone Watersheds* is available in digital format at www.gyclimate.org.

**Suggested citation for full report**

Hostetler S, Whitlock C, Shuman B, Liefert D, Drimal C, Bischke S. 2021. Greater Yellowstone climate assessment: past, present, and future climate change in greater Yellowstone watersheds Bozeman MT: Montana State University, Institute on Ecosystems. 260 p. https://doi.org/10.15788/GYCA2021.

# EXECUTIVE SUMMARY

The Greater Yellowstone Area (GYA) is one of the last remaining large and nearly intact temperate ecosystems on Earth. GYA was originally defined in the 1970s as the Greater Yellowstone Ecosystem, which encompassed the minimum range of the grizzly bear. The boundary now includes about 22 million acres (8.9 million ha) in northwestern Wyoming, south central Montana, and eastern Idaho (Figure ES-1). Two national parks, five national forests, three wildlife refuges, 20 counties, and state and private lands lie within the GYA boundary (Figure ES-1). The Tribal Nations of the Eastern Shoshone, Northern Arapaho, Apsáalooke/Crow, Northern Cheyenne, Shoshone, and Bannock have reservations in and near the Greater Yellowstone Area, and 27 Tribes are formally recognized to have historical connections to the lands and resources of the region. Natural resources sensitive to climate change connect many of the major economic activities of the GYA, including tourism and recreation, agriculture, and energy development.

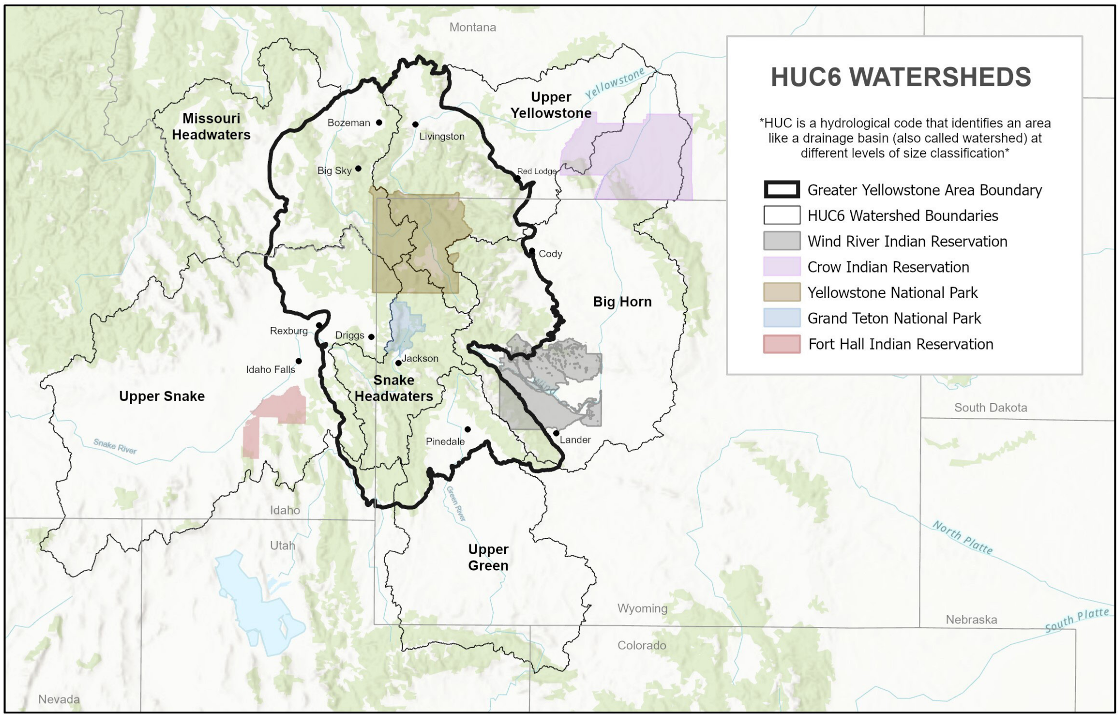



Figure ES-1. Map of the Greater Yellowstone Area (GYA) showing the six Hydrologic Unit Code 6 (HUC6) watersheds studied under the Assessment, and including mountain ranges, lakes and major river systems, jurisdictions, and selected towns. The portions of the watersheds within the GYA boundary are studied in this report. (Map created using ArcGIS® software, copyright ESRI and used herein under license.)

Humans are contributing substantially to global warming and climate change through greenhouse gas emissions, especially from the burning of fossil fuels. The leading science organizations around the world have issued public statements expressing this finding, including international and United States science academies, the United Nations Intergovernmental Panel on Climate Change, and a host of reputable scientific bodies.

The widespread consensus that the effects of climate change are increasingly apparent in all parts of the planet motivated us to analyze the potential impacts on the climate and water resources of the Greater Yellowstone Area.

# WHAT IS THE *GREATER YELLOWSTONE CLIMATE ASSESSMENT*?

This first volume of the *Greater Yellowstone Climate Assessment* ("the Assessment") presents an in-depth summary of past, historical, and projected future changes to temperature, precipitation, and water in the GYA. It is intended as a basis for further research and discussion of the important impacts and adaptation and mitigation opportunities related to climate change in the region. This Assessment, like others done at the international, national, and state levels, draws on the best science available at the time of writing (see box). To provide geographic detail to the analysis we focus on the GYA and six major river basins within the GYA.

# MAJOR FINDINGS

The major findings from the Assessment are summarized in Table ES-1. We provide additional details below. Estimates of confidence are provided for the key messages. They represent confidence that the specific data sets and model results examined here agree upon the direction of change and its significance (see Table 1-2 in the Assessment).

Table ES-1: Major findings of the *Greater Yellowstone Climate Assessment* for the Greater Yellowstone Area (GYA) and Hydrologic Unit Code 6 (HUC6) watersheds based on observations for the 1950-2018 historical period and projected changes to the year 2100. (RCP stands for *Representative Concentration Pathways*.)

| HUC6 Watershed | *Change between 1950-2018* | | | | *Trends to 2100 compared to 1986-2005 (based on MACAv2_METDATA[1] for RCP4.5)* | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Temperature | Snowfall | | Peak stream flow | Temperature | Precip-itation | Snowpack[2] | Jun - Aug runoff | Growing season length[3] |
| **GYA** | 2.3°F warmer | 23 inches less | 25% loss | 8 days earlier | 5.3°F warmer | 9% increase | 40% loss | 35% less | -- |
| **Upper Yellowstone** | 2.0°F warmer | 1.3 inches more | 1% gain | 12 days earlier | 5.2°F warmer | 9% increase | 44% loss | 36% less | 35 days longer |
| **Big Horn** | 0.89°F warmer | 7.3 inches less | 14% loss | 1 day earlier | 5.3°F warmer | 9% increase | 38% loss | 32% less | 40 days longer |
| **Upper Green** | 3.0°F warmer | 32 inches less | 44% loss | 4 days earlier | 5.4°F warmer | 10% increase | 38% loss | 33% less | 40 days longer |
| **Snake Headwaters** | 1.1°F warmer | 16 inches less | 11% loss | 15 days earlier | 5.5°F warmer | 9% increase | 39% loss | 38% less | 29 days longer |
| **Upper Snake** | 2.3°F warmer | 33 inches less | 32% loss | 12 days later | 5.4°F warmer | 8% increase | 41% loss | 39% less | 32 days longer |
| **Missouri Headwaters** | 2.6°F warmer | 4.1 inches more | 4% gain | 9 days earlier | 5.3°F warmer | 9% increase | 43% loss | 36% less | 28 days longer |

[1] The MACAv2-METDATA data set includes 20 global climate models that were statistically downscaled to a 4 km by 4 km (2.5 mile by 2.5 mile) grid using the Multivariate Adaptive Constructed Analogs method.

[2] Based on April 1st values.

[3] At towns in the major watersheds: Bozeman MT, Red Lodge MT, Cody WY, Pinedale WY, Jackson WY, Driggs ID. Base temperature is 45°F (7.2 °C), the germination temperature of wheat.

Historical data reveal how climate trends and extremes can vary geographically within the GYA, but future projections are constrained by the current geographic resolution of the models. Agreement in the future projections across watersheds (Table ES-1) likely underestimates future differences.

# How was the *Greater Yellowstone Climate Assessment* created?

***The objective***

The *Greater Yellowstone Climate Assessment* is intended to be a multi-phase effort to analyze and communicate information about climate change in the Greater Yellowstone region. The overarching goals of the Assessment are:

- to present understandable, science-based, and geographically specific information about the potential impacts of climate change on the people and resources of the region; and
- to provide a foundation of knowledge that helps the region prepare for and respond to climate changes occurring within the 21st century.

Water is fundamental for healthy ecosystems, and changes in climate and water affect ecosystem services (e.g., clean air and water, fish, wildlife, forests) in the GYA. The focus of this first volume of the Assessment is to summarize the causes and consequences of past and ongoing climate and hydrologic change on the watersheds of GYA, and to provide projections of future change.

This Assessment—like others done at the international, national, and state level—draws on the best science available at the time of writing to evaluate the state of climate change and its observed and potential impacts. We draw on the science expertise of partner universities, federal and state agencies, and non-governmental organizations, including Montana State University (Montana Institute on Ecosystems), University of Wyoming, Boise State University, US Geological Survey, Yellowstone and Grand Teton national parks, and Henry's Fork Foundation. An effort to listen to and engage the region's constituency was led by a team from the Greater Yellowstone Coalition, the Greater Yellowstone Coordinating Committee, National Park Service, the universities and extension services, and the Tribes in Wyoming, Idaho, and Montana.

Prior to release, the Assessment received scientific reviews from experts in the fields of climate, hydrology, and resource management. It also received input from citizens and organizations in the GYA during a period of public comment.

### *Our analysis*

We use the US Geological Survey Hydrologic Unit Code (HUC) watersheds to describe the region because the impact of climate change in the GYA is better characterized by natural geographic boundaries than by artificially defined borders such as state or national park boundaries. In the Assessment, we focus on the six major river basins that meet the definition of HUC level 6 (HUC6) classification: Missouri Headwaters, Upper Yellowstone, Big Horn, Upper Green, Snake Headwaters, and Upper Snake (Figures ES-1 ES-2).

In Chapter 1 we provide an introduction to the GYA and information on the structure of the report, including details on how we assign confidence to our findings. In Chapter 2 we present basic concepts of climate and climate change, summarize past climate and hydrologic changes in the GYA over the last 20,000 yr based on the geological record, and explain the natural and anthropogenic drivers of climate change. In Chapter 3, we examine observed 20$^{th}$- and early 21$^{st}$-century changes and trends in climate and water resources in the GYA based on weather station and streamgage measurements.

In Chapter 4, we provide an overview of the scientific methods used to develop projections of future changes in climate and water. In Chapters 5, 6, and 7, we present 21$^{st}$-century projections of air temperature, precipitation, and water, respectively, with a focus on climate variables that are relevant to agriculture, energy use, ecosystems, and winter recreation.

In Chapter 8, we offer some of the results of interviews with residents in the Greater Yellowstone Area, including their concerns for the future. In Chapter 9, we identify knowledge gaps and outline the next steps in the assessment process.

Dry periods in the past resulted in a near-century hiatus in eruptions of Old Faithful in the Upper Geyser Basin of Yellowstone National Park. This photo of Old Faithful was probably taken in 1878. (Photo credit: William Henry Jackson, USGS, public domain)

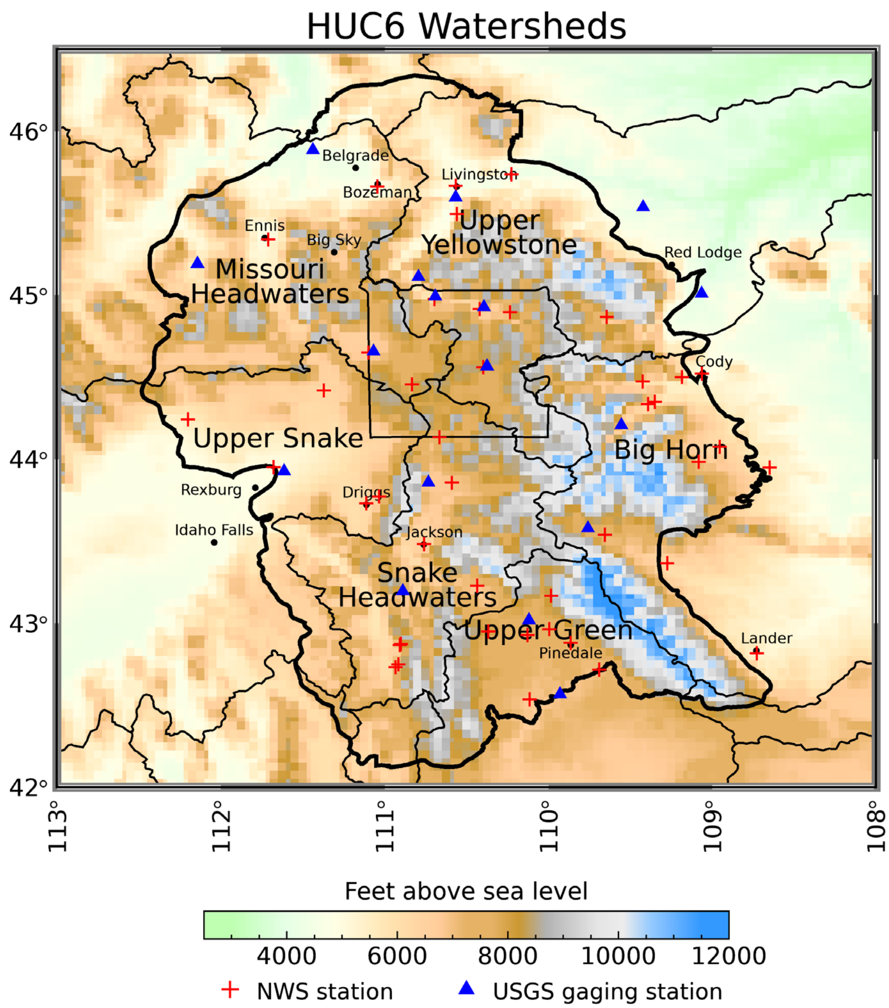



Figure ES-2. Location of National Weather Service (NWS) weather stations (red +) and US Geological Survey streamgaging stations (blue triangle) that provided the meteorological and streamflow records used in our analysis. We examine weather station data back to 1950 and streamflow data back to 1925.

## Temperature

### *Past perspective*

- GYA 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. Research suggests that the current level of carbon dioxide in the atmosphere is the highest in the last 3.3 million years. *[medium confidence]*
- Climate models can only capture the observed global temperature trend from 1880 to present by incorporating natural and anthropogenic drivers, including human-emitted atmospheric greenhouse gases. *[high confidence]*

### *Since 1950*

- o Meteorological records since 1950, averaged across the GYA, show that mean annual temperature in the GYA has increased by 2.3°F (1.3°C) at a rate of 0.35°F (0.20°C) per decade. *[high confidence]*

  Noteworthy:

  - The trends are large relative to typical warm- or cold-year departures from the average of 1.3°F (0.7°C) indicated by the standard deviation since 1950.
  - Warming has been more pronounced in spring than other seasons, particularly in March (Figure ES-3).
  - Mean annual temperatures in the Missouri Headwaters and Upper Snake watersheds are now similar to those of the Big Horn watershed, which historically was the warmest subregion of the GYA (Figure ES-3 and ES-4).
  - In the coolest watershed of the GYA, the Upper Green, annual average temperatures have risen from near freezing in the 1950s to the upper 30s°F (1–5°C) in the 2010s, causing a reduction in snowfall even though there has been little change in annual precipitation totals.

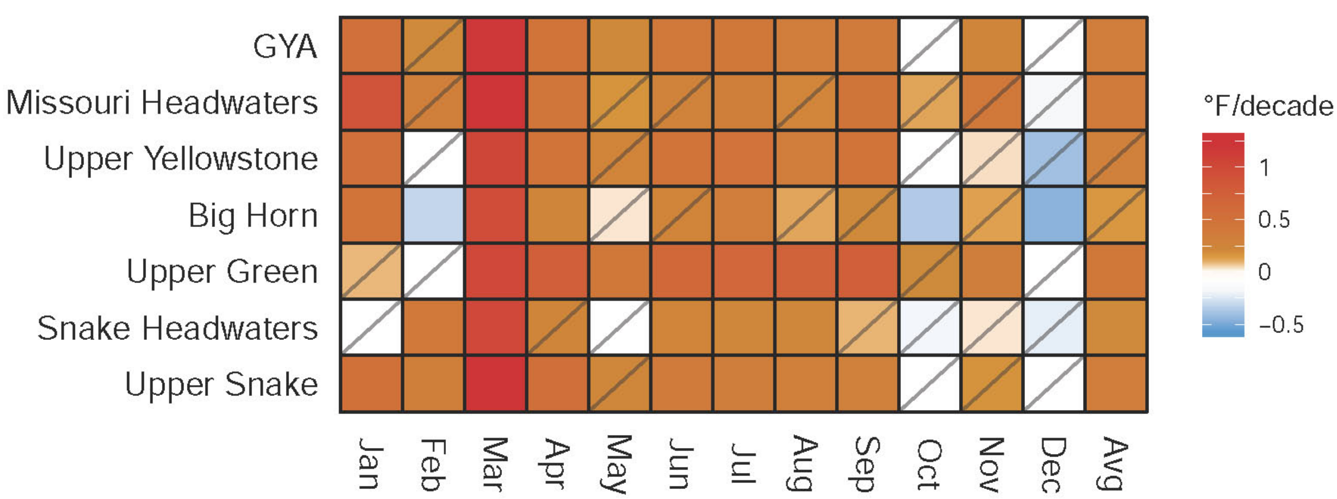



Figure ES-3. Temperature trends from 1950-2018 by watershed and month in the Greater Yellowstone Area (GYA). Boxes without slashes are statistically significant at the 95% confidence level. The last column (Avg) is the mean annual rate of change in each watershed.

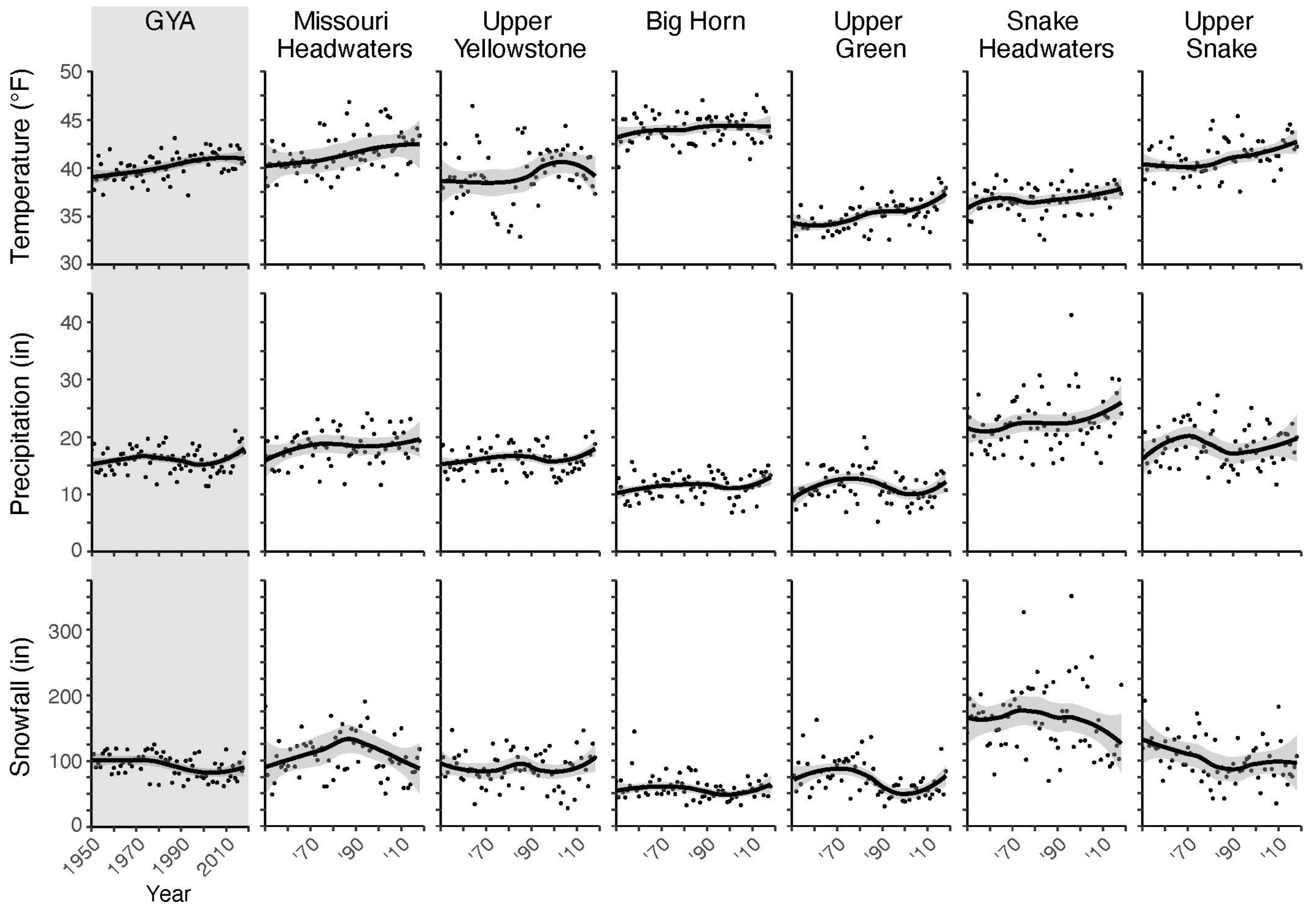



Figure ES-4. Annual temperature, total precipitation, and snowfall trends for the Greater Yellowstone Area (GYA) and Hydrologic Unit Code 6 (HUC6) watersheds since 1950. Each dot in the plots represents the mean annual value. The black lines are LOESS regressions fit to the point data and the gray shading indicates the 95% confidence level around the trend LOESS lines. The LOESS fits are used to highlight trends in the data.

## *Future*

In this report we consider two future greenhouse gas emission scenarios, known as *Representative Concentration Pathways* (RCPs) (see box, Figure ES-5). RCP4.5 describes a moderate greenhouse gas emission scenario assuming significant mitigation of emissions beginning in the next few years. RCP8.5 has little to no mitigation of greenhouse emissions and represents an extreme case. Projections reveal:

- Under RCP4.5 all four seasons warm relative to the 1986-2005 base period. Mean annual temperature in the GYA is projected to increase 5°F (3°C) by the period 2061-2080 and stabilize thereafter in response to expected mitigation (Figure ES-5). Under RCP8.5 all four seasons warm relative to the 1986-2005 base period and the GYA mean annual temperature is projected to increase by more than 10°F (5.6°C) by the end of the 21st century. *[high confidence]*

- By the end of the century, the number of hot days per year (high temperature above 90°F [32°C]) is projected to increase and exceed a week in Pinedale WY and a month in Cody WY under RCP4.5. Under RCP8.5, the number of hot days per year increases to nearly two months in Jackson WY and Pinedale WY and exceeds two months in Bozeman MT and Cody WY. *[high confidence]*

- By the end of the century, the number of cold days (low temperature below 32°F [0°C]) experienced by towns in the major watersheds is projected to decrease by about a month and a half under RCP4.5 and up to two and a half months under RCP8.5. *[high confidence]*

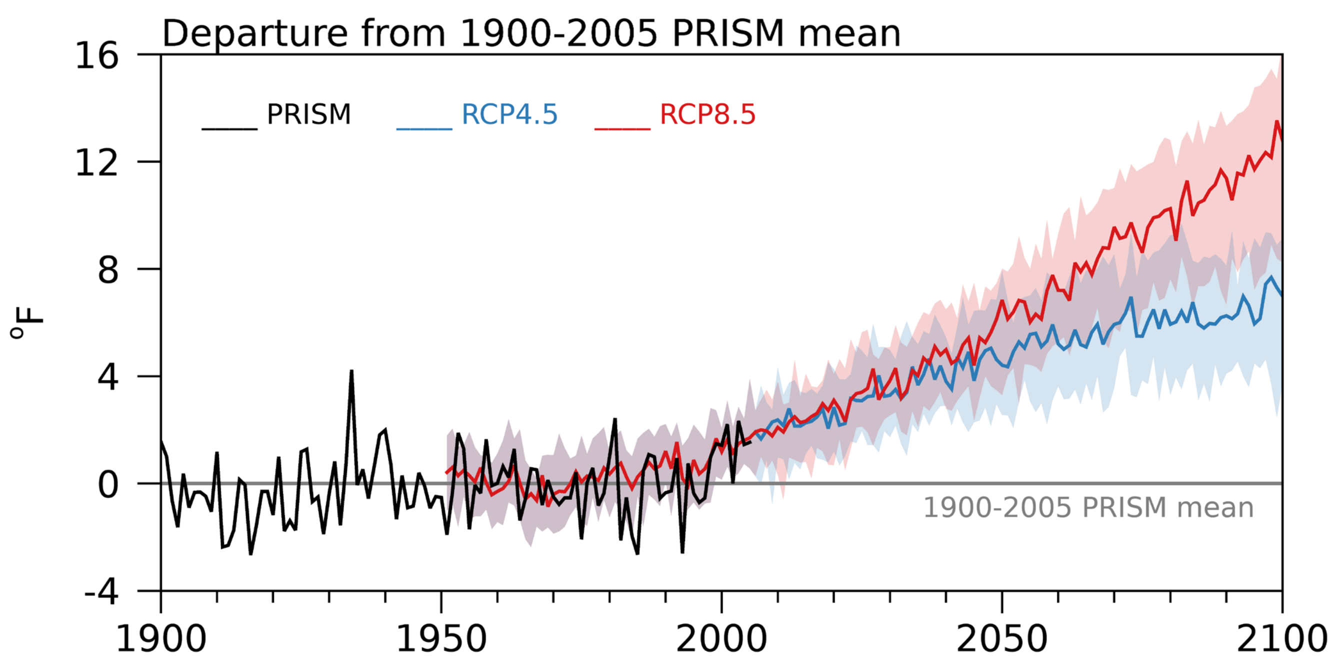
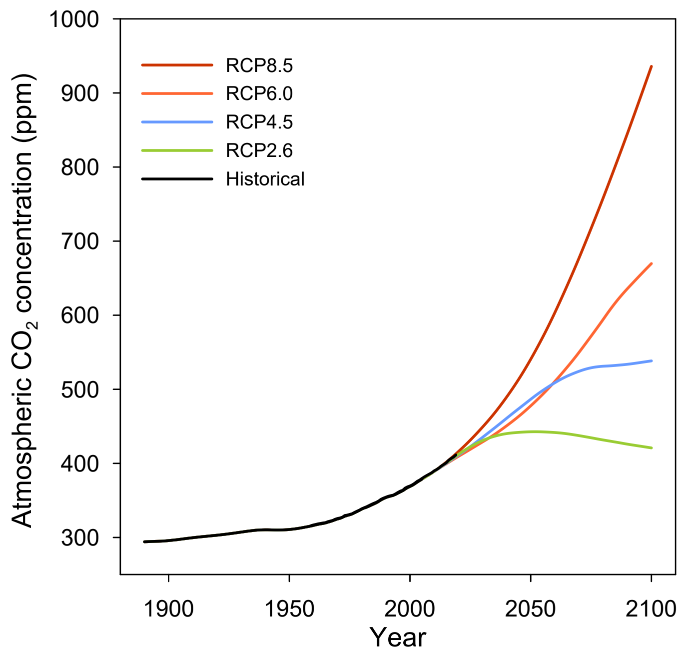



Figure ES-5. Historical and projected changes in the Greater Yellowstone Area annual temperature from 1900-2100 plotted as departures from the 1900-2005 PRISM mean (PRISM Climate Group undated). Historical changes in temperature (black line) are described in Chapter 2, and future projections from Representative Concentration Pathway 4.5 (RCP4.5, blue line) and RCP8.5 (red line) are described in Chapter 5. The colored lines for the RCP data are the median of 20 global climate model (GCMs) in the MACAv2-METDATA downscaled data set and the respective shaded bands around the lines are the 10th (lower) and 90th (upper) percentiles of the models.

# Future scenarios

The future climate scenarios we use in this Assessment were developed for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2013) and are called *Representative Concentration Pathways* (RCPs). RCPs are a reference to the extent that the accumulation of greenhouse gases (GHGs) and aerosols in the atmosphere affect the balance of incoming and outgoing energy in the Earth system. The number of an RCP indicates the amount of radiative forcing (in watts per square meter, or $W/m^2$) at the year 2100. The higher the RCP value, the greater the potential warming.

The RCPs bracket a range of plausible atmospheric GHG concentrations in the future based on various levels of emission reductions (mitigation), without assigning likelihood to any pathway. We base the Assessment on RCP4.5 and RCP8.5. RCP4.5 is an intermediate pathway that results in about 4.5°F (2.5°C) of global warming by the end of the century. RCP8.5 is an upper bound pathway that represents little or no mitigation in the coming decades and results in global warming of about 9°F (5°C) by the end of century. RCP4.5 and RCP8.5 are currently the most widely considered scenarios in climate change research.




Annual average atmospheric $CO_2$ concentrations. The black line combines reconstructed values from 1880-1958 and Mauna Loa observations from 1959-2019. The colored lines are the four Representative Concentration Pathway (RCP) scenarios used in the Fifth IPCC Assessment Report (2013). Mauna Loa observations retrieved from Scripps Institute (undated). RCP2.6 data from van Vuuren et al. (2007); RCP4.5 data from Smith and Wigley (2006), Clarke et al. (2007), and Wise et al. (2009); RCP6.0 data from Fujino et al. (2006) and Hijioka et al. (2008); RCP8.5 data from Riahi et al. (2007). These data sources are compiled at RCP Database (undated).

## Precipitation

### *Past perspective*

After the last extended dry period from 1905-1945, which included the 1930s Dust Bowl drought, mean annual precipitation in the GYA has been near to or above the long-term average with substantial year-to-year and decadal variability. For example, low precipitation in 1988 was followed by several years of high precipitation during the late 1990s and then very dry years in 2005 and 2016. The geologic record indicates that decade-long periods of low precipitation have occurred in the past 1200 yr. These dry periods were times of reduced snowpack, more fires, lower streamflow, establishment of trees above present tree line, and even a near-century hiatus in geyser activity of Old Faithful.

### *Since 1950*

- Average precipitation across the GYA has not changed significantly and remains near 15.9 inches (40.5 cm) with year-to-year variability of 2.2 inches (5.6 cm) based on the standard deviation of the meteorological record average. *[high confidence]*
- Precipitation has increased in spring and fall, by 17-23% in April and May, and 42% in October. It has declined by 17% in June and 11% in July. *[high confidence]*
- As climate has warmed, mean annual snowfall in the GYA has declined by 3.5 inches (8.9 cm) per decade. *[medium confidence]*

  Noteworthy: In the wettest watershed of the GYA, the Snake River headwaters, annual precipitation has increased, but annual snowfall has declined.
- Much of the snowfall decline has occurred in spring when warming was greatest. *[high confidence]*

  Noteworthy:

  - Measurable snowfall has become rare in June and September as the snow-free season has lengthened.
  - Average snowfall at weather stations in the GYA used to be highest between 6000–7000 ft (1800-2100 m) elevation, but since 1950, snowfall in this elevation range has declined markedly even as total annual precipitation has remained the same or increased. The decline has occurred because mean temperature has risen by 2.5°F (1.4°C) since the 1980s over those elevations, which converted precipitation from snow to rain.

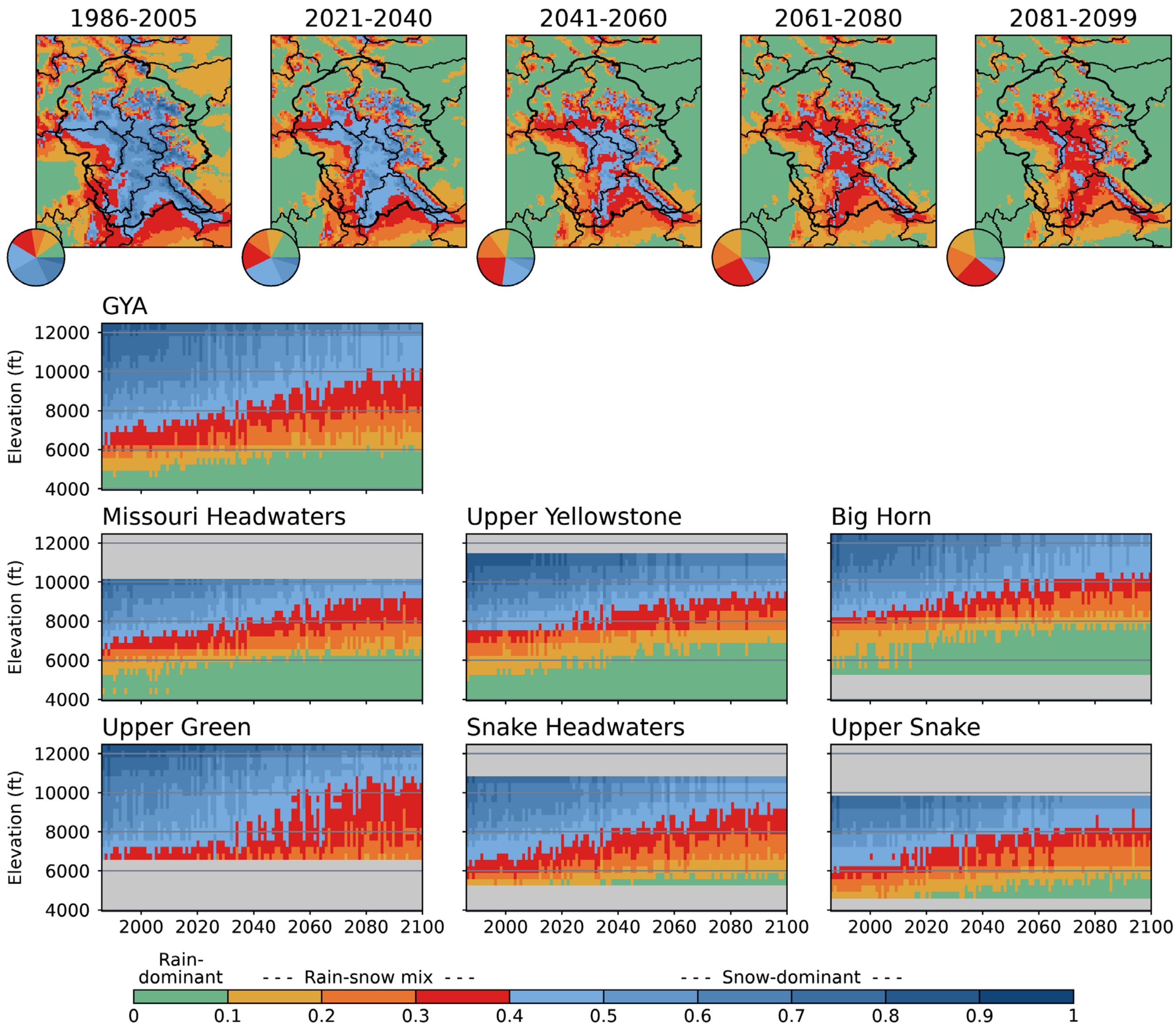



Figure ES-6. The 1986-2099 annual snow regime for the Greater Yellowstone Area (GYA) and Hydrologic Unit Code 6 (HUC6) watersheds under RCP4.5. The five maps across the top display SWE:P, which is the ratio of snow (measured as snow water equivalent [SWE]) to rain during the cold-season (Oct-Apr). The pie charts inset in the maps show the fraction of the GYA within each snow-to-rain category. The time-elevation plots for the HUC6 watersheds in the bottom two rows display the trend in each category from 1986-2099 averaged over 330 ft (100 m) elevation bands. Gray shading indicates elevations not present in the HUCs. (The appendix to Chapter 7 provides more details on the SWE:P ratio, and the related figure for Representative Concentration Pathway 8.5 [RCP8.5].)

## *Future*

- o Under RCP4.5, mean annual precipitation in the GYA is projected to increase 7% by mid century (2041-2060) and 8% by the end of century (2081-2099) relative to the 1986-2005 base period. Under RCP8.5, the projected increases are 9% and 15% for these periods, respectively. *[high confidence]*
- o The projected increase in mean annual precipitation is attributed to increases during the December through April cold season, particularly in March and April when the snow-to-rain transition occurs. *[high confidence]*
- o By the end of the century (2081-2099), the wettest month shifts from May to April in the Big Horn, Upper Green, and Snake Headwaters HUC6 watersheds. These shifts occur by mid century (2061-2080) and are amplified under RCP8.5. *[medium confidence]*
- o Under RCP4.5, the total area of the GYA dominated by winter snowfall decreases from 59% during the base period (1986-2005) to 27% mid century (2041-2060) and to 11% by the end of century (2081-2099). Under RCP8.5, the extent of snow-dominant area decreases to 17% and to 1% for the same time periods, respectively (Figure ES-6) *[high confidence, statistical significance of the trends]*. These changes result in a decrease in the amount of water stored as annual snowpack (Figure ES-7).

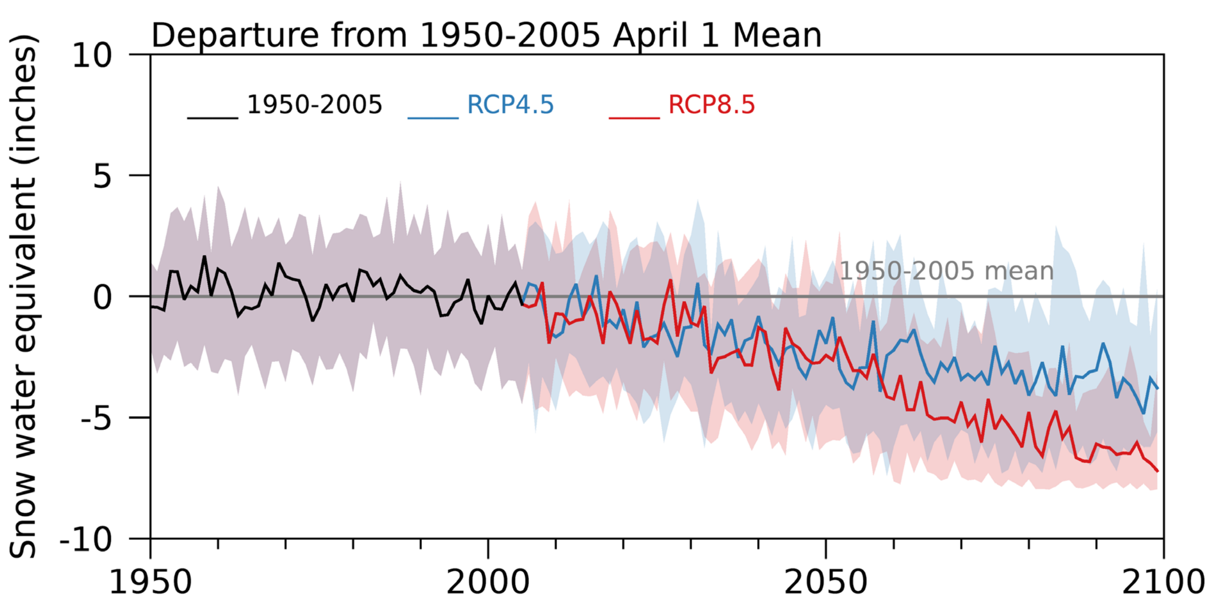



Figure ES-7. Changes in the amount of water (SWE) stored in the April 1 snowpack in the Greater Yellowstone Area relative to the 1950-2005 mean as simulated by the water balance model used in the Assessment. Historical changes (black line), Representative Concentration Pathway 4.5 (RCP4.5, blue line), and RCP8.5 (red line) are the median change for the 20 global climate models (GCMs) in the MACAv2-METDATA data set as described in Chapter 7. The respective shaded bands around the lines are the 10$^{th}$ (lower) and 90$^{th}$ (upper) percentiles of the models.

## Streamflow, runoff, and soil water deficit

Streamflow records in the GYA since the early 20th century allow comparison of current trends to past events such as the 1930s Dust Bowl drought. Hydrologic simulations enable projections of streamflow, runoff, and soil moisture based on the climate projections.

### *Since 1925*

- Annual streamflow today is similar to that of the mid-20th century, but on average over the GYA the timing of peak flow has shifted earlier in the year by 8 days (range of 1-15 days in the HUC6 watersheds), extending the length of the water-limited warm season. *[high confidence]*

  Noteworthy:

  - The shift in the timing of peak streamflow since 1970 has been approaching the early timing that occurred during the 1930s Dust Bowl drought. The recent shift, however, is caused by rising spring temperatures that melt snow earlier, whereas during the Dust Bowl drought it was caused by a year-round decline in precipitation.

Bison on Yellowstone's Northern Range
Photo courtesy of Cindy Goeddel

- The volume of streamflow in most of the rivers has changed little relative to the average conditions of the last 95 yr, but increases in some rivers, such as the Yellowstone, Gallatin, and Madison, contribute to a regional average increase in streamflow of less than 10% since 1925.
- In selected free-flowing rivers within the GYA, annual flows since the mid-20th century have decreased by 3-11%, spring flows have increased by 30-80%, and summer and fall minimum flows have declined by 10-40% (Figure ES-8).

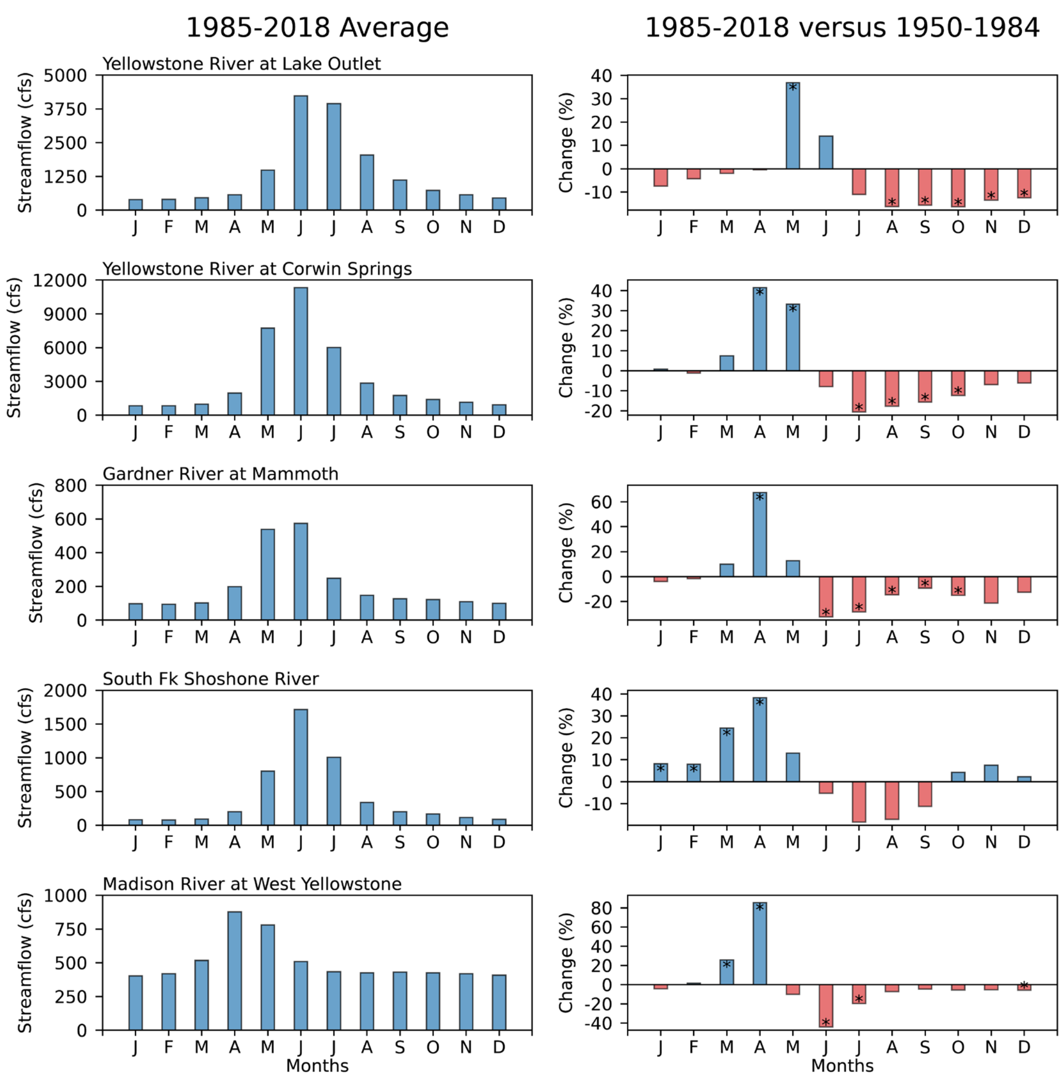



Figure ES-8. Monthly mean streamflow in free-flowing rivers in the Greater Yellowstone Area from 1985-2018 (left column), and percent changes from the 1950-1984 average (right column; the averaging period for the South Fork Shoshone is 1960-1989). The asterisks indicate changes that are statistically significant at a 90% level (based on a means t-test). The inset numbers are the percent change in mean annual flow. The rivers are selected based on USGS streamgages identified in the USGS Hydro-Climate Data Network as having little or no human impact on natural flow (Lins 2012).

### *Future*

- o Total annual runoff in the GYA is projected to increase by about 1% by mid century (2041-2060) and by 2% at the end of century (2081-2099) under RCP4.5 and increase by 2% and 3% for same time periods, respectively, under RCP8.5. *[low to medium confidence]*

- o The seasonality of runoff is projected to change as snowfall declines and snowpack melts earlier under both RCP4.5 and RCP8.5. *[high confidence]*

  Noteworthy:

  - The biggest changes will be at mid- and high elevations where runoff from snowmelt increases in spring (March through May) and decreases in summer (June through August).

  - Timing of peak runoff is projected to shift 1-2 months earlier in the year in the later part of the century under RCP8.5.

- o On an annual basis, precipitation (P) over the GYA exceeds potential evapotranspiration (PET), but the reverse is true in summer, particularly at lower elevations, leading to a seasonal water deficit that is projected to increase in the future. *[high confidence, statistical significance of the trends]*

  Noteworthy: Under RCP4.5, the summer water deficit is projected to increase by 25% mid century and by 36% by the end of century. Under RCP8.5, projected deficit increases are 35% by mid century and 79% by the end of century.

- o Under RCP4.5 June-October soil moisture saturation decreases by 23% by mid century and 33% by the end of the century. Under RCP8.5 June-October soil moisture saturation decreases by 30% mid century and 56% by the end of the century. *[high confidence]*

  Noteworthy: The declines will reduce already limited soil moisture in summer, which in recent decades (1986-2005) has reached about 25% of capacity at low elevations of the GYA and about 50% of capacity at higher elevations.

# IMPLICATIONS FOR THE REGION

## Agriculture

The growing season in the GYA—based on temperature and as represented by the towns in the watersheds (Table ES-1)—is about 2 weeks longer now than it was in the 1950s and is projected to be longer and warmer in the future. Recent climate assessments for the Northern Great Plains (Conant et al. 2018) and Montana (Whitlock et al. 2017) suggest the likelihood of both positive and negative impacts on regional agriculture in the future, but the high elevation and diverse topography of the GYA may be somewhat buffered from the negative impacts that are projected, for example, in the Great Plains. The greenhouse effect of elevated $CO_2$ levels offers the opportunity to grow new plant varieties, and the likelihood of earlier green-up means an earlier grazing season. Still, while some crops and livestock may benefit from longer, warmer growing seasons in the GYA, irrigated and non-irrigated production will need to accommodate earlier snowmelt and timing of runoff and reduced late-season soil moisture. Warmer conditions may also decrease forage quality and support an increase in crop pests.

## Energy

Future warming in winter will decrease annual heating degree days in the GYA, which will lessen energy demand for commercial and home heating. Relative to the 1986-2005 base period, under RCP4.5 heating degree days decrease by 13% by mid century (2041-2060) and decrease by 14% by the end of century (2080-2099) (Figure ES-9). Under RCP8.5, decreases are 16 and 31% for the two periods, respectively. By mid century, under both RCPs the projected decrease in heating degree days in the towns is roughly five times greater than the increase in cooling degree days, which would mean less annual energy use in the future.

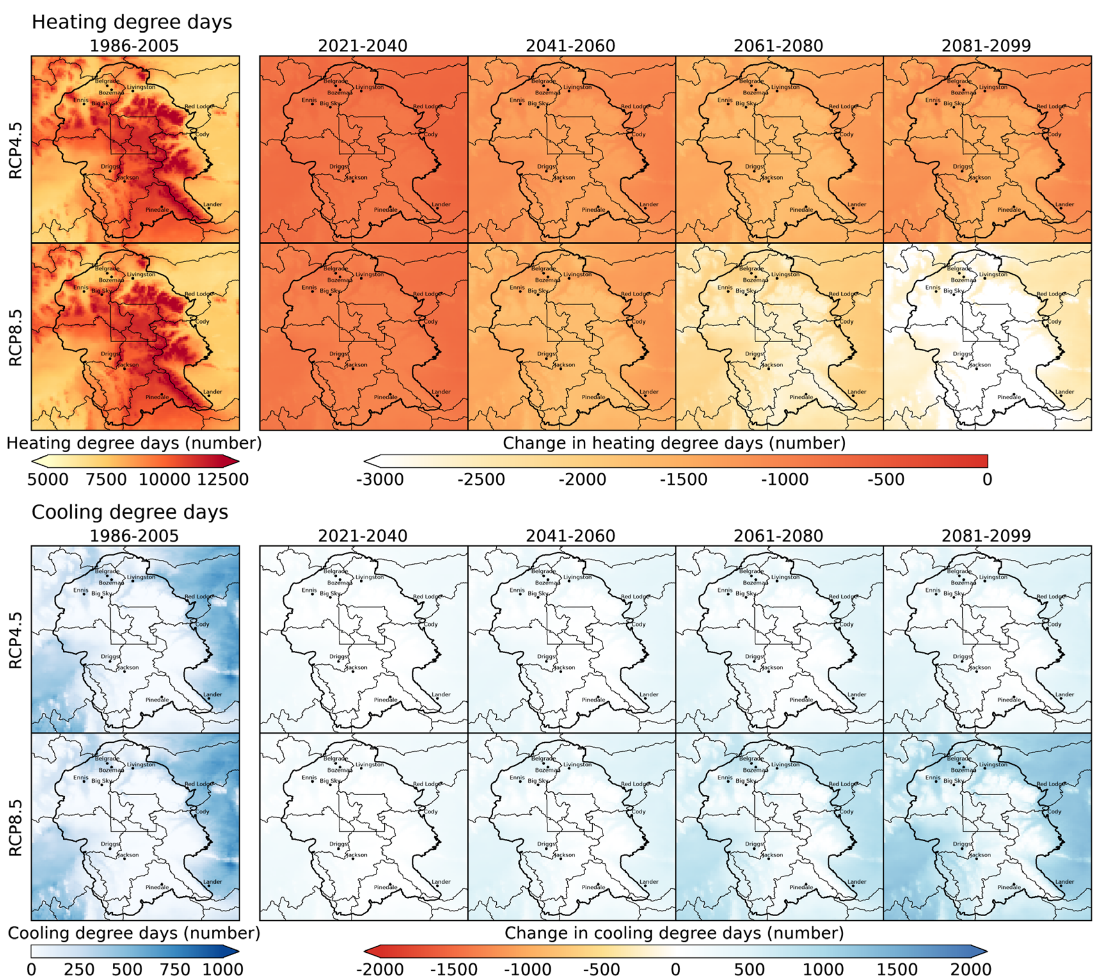



Figure ES-9. Annual number of heating degree days (top two rows) and cooling degree days (bottom two rows) in the Greater Yellowstone Area. The 1986-2005 base periods are shown in the left column and changes for the four future periods are shown to the right. The mapped data are computed from MACAv2-METDATA daily average minimum temperature (heating degree days) and daily average maximum temperature (cooling degree days).

## Wildfire

In the future, earlier snowmelt and loss of snowpack, as a result of warming winters, followed by warmer summers, longer growing seasons, and reduced water availability will increase fire potential at all elevations of the GYA (Westerling et al. 2011). This condition, combined with increased tree mortality, potentially could alter future fire regimes and lead to rapid changes in forest ecosystems. Sustained changes in climate and fire disturbance will also affect the recovery of species after fire, changing forest composition, and possibly converting forest to grassland at low elevations. Thus, increased fire activity portends large ecological changes and threatens human health and the communities in the GYA.

## Winter recreation

Decreases in snowpack are projected to continue in the future. Even though precipitation is projected to increase, as winters warm, a smaller portion of precipitation will fall as snow and more will be a mixture of rain and snow, particularly in March and April when the snow-rain transition now occurs. Under RCP4.5, mid-century loss of snowpack ranges between 24-31% of 1986-2005 levels and reaches 38-44% by the end of century. Losses are greater under the warmer conditions of RCP8.5. Elevational changes in snow will affect most aspects of winter recreation in the GYA. In Yellowstone National Park, for example, Tercek and Rodman (2015) found that the length of the snow season at the end of century (2061-2090) could decline by 16 and 27% from present under RCP4.5 and RCP8.5, respectively, with similar or greater declines in the number of days suitable for over-snow vehicles. Lackner et al. (2021) project that under RCP8.5 the number of ski days in 2050 will be reduced by from 6 to 29 days at ski areas within the GYA.

# CONCERNS FROM STAKEHOLDERS

The GYA is home to a great diversity of species and environments and a rich variety of cultures. Interviews conducted with 44 stakeholders throughout the GYA yielded important insights into the climate realities faced by local communities. Participants spoke about their perspectives on climate change, providing their concerns, observations, and priorities for the future. The following key findings emerged from these conversations:

- Water issues are at the core of climate change impacts in the GYA. Communities and managers will continue to face challenges like drought and shifts in seasonal water cycles in the future.
- Participants' understanding of and response to climate change is driven more by their background (stakeholder group) than their location (watershed).
- A pressing need exists for a climate information hub that is comprehensive, collaborative, accessible, and useful to experts and the public alike.
- For the most part, meaningful policy to address and adapt to climate change is lacking in the GYA.
- By addressing water issues like availability and quality in future climate adaptation work, we stand to have positive impacts on myriad other conditions including wildlife habitat, fisheries health, and the economy of local communities.

Photos courtesy of, from left to right: #1,4 Greater Yellowstone Coalition; #2 Charles Wolf Drimal; #3 Bryan Shuman

# CONCLUSIONS

This first-phase Assessment provides an overview of the potential impacts of climate change in GYA watersheds. It is intended as a starting point for future assessments focused on related topics, including impacts on water, fish and wildlife, local economies and communities, and human health in the GYA.

We conclude the report by identifying some of the important gaps in our scientific understanding of climate change in the GYA. We also highlight needs for climate adaptation efforts. These lists are not exhaustive and but are intended to highlight issues we believe deserve attention in future assessments and planning efforts.

## Science and monitoring needs

- Provide regular updates of the *Greater Yellowstone Climate Assessment* that incorporate the latest climate projections consistent with those developed at the national and international level.
- Develop and apply more detailed models of snow processes, groundwater, surface water, and ecosystem and human water demand to refine our understanding of water and water use in the GYA. Modeling potentially complex local changes in water supply, demand, and their interactions will require improved representations of the underlying processes in each watershed.
- Maintain and expand monitoring of snow, streams, lakes, and wetlands within GYA watersheds. Currently, weather stations and streamgages are unevenly distributed in the GYA, few water bodies and wetlands are monitored, particularly at high elevations, and water demand for ecosystems and for human use and consumption is poorly measured.
- Quantify the connections between climate change, the carbon cycle, urbanization, agricultural practices, and biodiversity in the GYA. This information will help identify opportunities to maintain valued ecosystem qualities and services, sustain essential economic and cultural uses, and increase carbon storage on natural and managed lands.
- Continue to expand monitoring efforts of fish and wildlife to improve our understanding of their changing behavior, disease, and distribution in response to climate change.
- Continue to improve our understanding of the linkages between long-term trends in fire climate and short-term fire weather and fuel conditions.

- Support studies of forest health, including the impact of climate change on insect outbreaks, wildfire activity, drought-caused mortality, and carbon storage to guide appropriate management planning.
- Quantify how climate change in the GYA will affect vital ecosystem services, including air quality, water quality and quantity, food, timber, and biodiversity.

## Climate adaptation needs

- Expand efforts to engage regional stakeholders on the topic of climate change through listening sessions and other exchanges that help find common ground for effective watershed and community planning. Establish effective ways to share information from new scientific studies and from monitoring and evaluation efforts so that it is available to all stakeholders in a timely way.
- Work with communities and water management districts to identify the local consequences of climate change, as a step toward developing implementing adaptation plans. On tribal lands, sustaining traditional subsistence, ceremonial, and medicinal resources is also important. Identify cross-jurisdictional challenges early in the process, so that planning efforts are effective and efficient.
- Develop a list of at-risk habitats and specific indicators of ecological and human health to be studied and monitored to help resource managers maintain a robust baseline for measuring change and assessing the effectiveness of adaptation measures.
- Evaluate the effects of projected climate change on the economies of the GYA: tourism and recreation, hunting and fishing, agriculture and forestry, and mineral and energy resource extraction as part of a sustained Assessment effort.


Arapaho Color Guard at Northern Arapaho bison release in 2019, Ethete WY
Photo courtesy of Crystal C'Bearing

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*Back cover: Teton Range, in smoky haze after sundown, near Moran, Wyoming. Photo courtesy of Steven Hostetler*

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Sprinkler irrigation on a potato field east of Ashton ID
Photo courtesy of Brian Apple (Henry's Fork Foundation)

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