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

6. FUTURE PRECIPITATION PROJECTIONS FOR THE GREATER YELLOWSTONE AREA

Steven Hostetler and Jay Alder

Key Messages

- 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. [medium confidence, >80% model agreement and SNR >1]

- 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-rain transition occurs. [high confidence, >80% model agreement and SNR >1]

- 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 watersheds. These shifts occur by mid century (2061-2080) and are amplified under RCP8.5. [medium confidence, 60-80% model agreement]

- In the HUC6 watersheds, statistically significant positive trends in mean annual precipitation range from 0.17-0.23 inches/decade (0.43-0.58 cm/decade) under RCP4.5, and 0.35-0.52 inches/decade (0.89-1.3 cm/decade) under RCP8.5. Given the spread in the models, RCP4.5 and RCP8.5 trends are not significantly different over the 21st century. [medium confidence, significance in trends]

Introduction

In this chapter, we analyze projected changes in mean annual, seasonal, and monthly precipitation in the GYA and the HUC6 watersheds. We summarize the main points of the projections and provide the details of the projections through time and space with interrelated maps, graphs, and checkerboard plots.
Annul and Seasonal Precipitation Over the GYA

The distribution of precipitation over GYA is influenced by the direction from which the moisture arrives, which varies seasonally and topographically (see Chapter 2). As evident in Figure 6-1, that influence is particularly strong during the winter and spring when most precipitation falls as snow at higher elevations. Under RCP4.5, projected mean annual precipitation over GYA increases by 1.4 inches (3.6 cm; 5.4%) over the 2021-2040 period to 2.4 inches (6.1 cm; 9.0%) in 2080-2099. Under RCP8.5, the increases for these periods are 1.6 inches (4.1 cm; 6.0%) and 3.9 inches (9.9 cm; 14.6%). Throughout the 21st century, the largest increase for both RCPs is in spring (MAM) followed by winter (DJF). During summer, the changes range from small increases (0.1 inches [0.3 cm]; 2.2%) to small decreases (-0.2 inches [-0.5 cm]; 2.8%). Fall precipitation increases somewhat until 2060 and decreases thereafter. A 1 inch (2.5-cm) change in precipitation over the entire GYA amounts to roughly 1,000,000 acre-ft (123,348,000 m³) of water.¹

![Figure 6-1](image)

Figure 6-1. Seasonal mean precipitation in the Greater Yellowstone Area for the 1986-2005 base period (left column), changes under Representative Concentration Pathway 4.5 (RCP4.5, four center columns), and the end of the 21st century under RCP8.5 (right column). The seasons (e.g., December-February [DJF]) are arranged in rows and the differences relative to the 1986-2005 base period for each future period (e.g., 2021-2040) are in columns. The data shown are the 20-model means of the MACAv2-METDATA. See Figure A6-1 in the appendix to this chapter for all RCP8.5 maps.

¹ For comparison, the volume of Yellowstone Lake is just over 12,000,000 acre-ft (14,801,760,000 m³) (NPS undated).
There is little change in the projected maximum length of wet spells under either RCP4.5 or RCP8.5 across the GYA (Figure 6-2). There is also little projected change in the maximum length of dry spells. As indicated by the increased upper portion of the shaded bands, after 2050 some models simulate an increase in the number of days for the maximum dry spell length under RCP8.5.

Figure 6-2. Length of wet spells A) and B) and dry spells C) and D) in the Greater Yellowstone Area under Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5. The heavy lines are the 20-model median and the shaded bands indicate the 10th (bottom) to 90th (top) percentiles around the medians. The black portion is the 1950-2005 period and the colored portion is for the RCP simulations (2006-2099). Indexes are calculated from the MACAv2-METDATA precipitation data. See Table A6-1 in the Appendix for details of how wet and dry spells are calculated.
Precipitation Over the HUC6 Watersheds

For the 1986-2005 base period, mean annual precipitation in the GYA ranges from 22 inches (56 cm) in the Upper Green watershed to 31 inches (79 cm) in the Snake Headwaters watershed (Figure 6-3 and Table 6-1). The positive trend between 1950 and 2005 (here and in Chapter 3) continues under both RCPs. The trends are statistically significant at the 95% confidence level in all HUC6 watersheds under both RCPs. Although the amount of annual precipitation varies among the HUC6 watersheds, as indicated by the inset numbers, the trends (in inches/decade) are similar. Under RCP8.5, the projected trends are roughly twice those of RCP4.5. The precipitation trends are more gradual than those of temperature described in Chapter 5 and the annual values of the RCPs are not statistically different, as indicated by overlap of the medians and the range and overlap of the shaded bands.

Figure 6-3. Time-series plots of the 1950-2099 mean annual precipitation for the Hydrologic Unit Code 6 (HUC6) watersheds. The solid lines are the medians of the 20 models in the MACAv2-METDATA data, from 1950-2005 (black line), and 2006-2099 for Representative Concentration Pathway 4.5 (RCP4.5, blue line) and RCP8.5 (red line). The shaded bands around the lines are the 10th (lower) and 90th (upper) percentiles of the models. The first number in the inset in each panel is the trend (in inches/decade) for RCP4.5 and the second number is the trend for RCP8.5. An asterisk indicates that the trend is statistically significant at a 95% confidence level.
Relative to the 1986-2005 base period, under RCP4.5 projected mean annual precipitation in the GYA is 7% greater by mid century (2041-2060) and 8% greater at the end of century (2081-2099) (Table 6-1). Under RCP8.5, the projected increases are 9 and 15% for these periods, respectively. The increases are essentially uniformly distributed over the HUC6 watersheds. Again, the absolute changes are relatively small but represent a substantial amount of water when totaled over the area of a HUC or the GYA.

Table 6-1. Mean annual precipitation in the Greater Yellowstone Area (GYA) and Hydrologic Unit Code 6 (HUC6) watersheds for the 1986-2005 base period and change during the four future periods under Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5. The units are in inches and the parenthetical values are percent change.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Base period precipitation, inches</th>
<th>Change in precipitation, RCP4.5</th>
<th>Change in precipitation, RCP8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>GYA</td>
<td>26.7</td>
<td>1.4 (5%)</td>
<td>1.8 (7%)</td>
</tr>
<tr>
<td>Missouri Headwaters</td>
<td>25.7</td>
<td>1.4 (6%)</td>
<td>1.6 (6%)</td>
</tr>
<tr>
<td>Upper Yellowstone</td>
<td>28.2</td>
<td>1.6 (5%)</td>
<td>1.8 (6%)</td>
</tr>
<tr>
<td>Big Horn</td>
<td>23.2</td>
<td>1.3 (5%)</td>
<td>1.8 (6%)</td>
</tr>
<tr>
<td>Upper Green</td>
<td>22.1</td>
<td>1.2 (5%)</td>
<td>1.6 (7%)</td>
</tr>
<tr>
<td>Snake Headwaters</td>
<td>31.2</td>
<td>1.6 (5%)</td>
<td>2.0 (6%)</td>
</tr>
<tr>
<td>Upper Snake</td>
<td>27.2</td>
<td>1.5 (5%)</td>
<td>1.8 (6%)</td>
</tr>
</tbody>
</table>
THE SEASONAL CYCLE OF PRECIPITATION

Projected mean monthly precipitation across the HUC6 watersheds, like mean annual precipitation across the GYA, shows the influence of topography and varies by season (Figure 6-4). For the 1986-2005 base period, May is the wettest month in the GYA. Over the northern and eastern watersheds (Missouri Headwaters, Upper Yellowstone, and Big Horn), precipitation increases throughout the winter and peaks in May before declining to summer minima (Figure 6-4). The southern and western watersheds (Upper Green, Snake Headwaters, and Upper Snake) receive more-or-less uniform precipitation throughout winter and spring before it declines to summer minima after May. As shown in Figure 6-4, under RCP4.5 an increase in January through April precipitation becomes greater through the century and, 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 watersheds. These shifts occur by mid century (2061-2080) and are amplified under RCP8.5. This projected change in the seasonality of precipitation contributes to altering the timing of future runoff.

Under RCP4.5 an increase in January through April precipitation becomes greater through the century and, 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 watersheds. These shifts occur by mid century (2061-2080) and are amplified under RCP8.5. This projected change in the seasonality of precipitation contributes to altering the timing of future runoff.
Figure 6-4. The seasonal cycle of mean monthly precipitation for the Hydrologic Unit Code 6 (HUC6) watersheds under Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5. The black line shows 1986-2005 base period. The colored lines are the 20-model means of the MACAv2-METDATA data for the periods indicated in the legend at the bottom. The shaded bands are the model spread around the respective colored mean lines.
Checkerboard plots for the HUC6 watersheds and the GYA (Figure 6-5) further illustrate the nature of the projected 21st-century precipitation changes. As in Figure 5-6, each rectangular grid in Figure 6-5 illustrates the differences (anomalies) between a given period and the base period (e.g., 2021-2040 minus 1986-2005) broken down by monthly and annual means, for the GYA and each HUC6 watershed.

Changes in mean monthly precipitation are more variable both among HUC6 watersheds and between RCPs than is the case with temperature (Figures 5-5, 5-6, 5-7). The four time periods all show increases in cold season (November through April) precipitation. The number of boxes displaying model agreement and SNRs >1 increases through time as the magnitude of future changes become greater. Subtle differences across the HUC6 watersheds for a given month reflect spatial differences in precipitation shown in Figure 6-1.

Figure 6-5. Change in projected mean monthly and annual precipitation in the Greater Yellowstone Area (GYA) and Hydrologic Unit Code 6 (HUC6) watersheds. The columns from left to right show changes for each future period (e.g., 2021-2040) relative to the 1986-2005 base period with Representative Concentration Pathway 4.5 (RCP4.5) on the top row and RCP8.5 on the bottom row. In each RCP figure, the months and annual mean (AVG) run from left to right across the horizontal axis on the bottom and the HUC6 watersheds and GYA run along the vertical axis on the left. Colored cells indicate >80% (more than 16 of the 20 models) agree on the sign of the change in the median value (positive or negative). A slash in a colored cell indicates that 60-80% of the models (12-16 out of 20) agree on the sign of the change, and an X in a box indicates that fewer than 60% (<12) of the models agree on the sign of the change. A black dot in a box indicates that the ensemble mean value of the future change is greater than the inter-model standard deviation (SNR >1), an indicator of significance of the change (see Chapter 1 for details). The data shown are the 20-model means of the MACAv2-METDATA data.
From June through October, precipitation changes are mixed in sign and vary by HUC6 watershed. Slightly more drying is evident in the northern and eastern watersheds. There is less agreement of the projected change among the models than there is during the cold season and no boxes display SNR >1. Lack of significance and model agreement is attributed to the wide range of summer precipitation simulated by the 20 GCMs (Figure A6-2). While projected increases in winter and spring are consistent among models, projections for the warm season (June through October) are a mix of increases, decreases, and no change that vary by climate model and watershed. Decreased precipitation in summer and increased precipitation in fall in some HUC6 watersheds are consistent with observed trends since 1950 (see Chapter 3). Seasonal contrasts in model agreement and model spread suggest that the underlying mechanisms of winter precipitation (e.g., changes in storm tracks and greater capacity for a warming atmosphere to hold moisture) are shared among the models, whereas the primary form of summer precipitation (convection) is more challenging to model and less consistent among models. It also reveals limitations in the ability to statistically downscale convective precipitation.

Summary of Projected Precipitation Changes

- Under both RCP4.5 and RCP8.5, there is a high level of model agreement in the projected increase in mean annual precipitation over the GYA and the HUC6 watersheds. The increase is attributed to increases in winter and spring. [85 to 100% model agreement and SNRs >1]

- Under both RCP4.5 and RCP8.5, the models project a mix of increases and decreases in summer precipitation with generally less than 60% model agreement. There are no SNRs >1 in the projected changes in summer precipitation.

- There is little change in the projected length of wet spells under either RCP4.5 or RCP8.5 across the GYA (Figure 6-2). There is also little projected change in the maximum length of dry spells; however, after 2050 some models simulate an increase in the length of dry spells under RCP8.5.

- Statistically significant positive trends in mean annual precipitation are projected for all HUC6 watersheds under both RCP4.5 and RCP8.5, but the trends for the RCPs are not statistically different.


**Chapter 6 Appendix—A Deeper Look**

Table and figures supporting Chapter 6

Table A6-1. The climate variables discussed in this chapter.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Source</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet spell</td>
<td>Maximum number of consecutive days/yr with daily precipitation amounts of at least a trace (≥1 mm).</td>
<td>Derived from MACAv2-METDATA</td>
<td>Days</td>
</tr>
<tr>
<td>Dry spell</td>
<td>Maximum number of consecutive days/yr with daily precipitation amounts of less than a trace (&lt;1 mm).</td>
<td>Derived from MACAv2-METDATA</td>
<td>Days</td>
</tr>
</tbody>
</table>

Figure A6-1. Seasonal mean precipitation in the Greater Yellowstone Area for the 1986-2005 base period (left column), changes under Representative Concentration Pathway 8.5 (RCP8.5, four center columns), and the end of the 21st century under RCP4.5 (right column). The seasons (e.g., December-February [DJF]) are arranged in rows from top to bottom and the changes relative to the 1986-2005 base period for each future period (e.g., 2021-2040) are in columns. The data shown are the 20-model means of the MACAv2-METDATA data.
Figure A6-2. The range of projected change in seasonal mean precipitation under Representative Concentration Pathway 8.5 (RCP8.5) for the Hydrologic Unit Code 6 (HUC6) watersheds, as simulated individually by the 20 downscaled global climate models (GCMs) in the MACav2-METDATA. The seasons are in columns and the future period are in rows. Within each block of the GCM names and their mean (Mean Model) are labeled on the left and the HUC6 basins are labeled at the bottom. See Table A4-1 for model details.