MCA
MONTANA CLIMATE ASSESSMENT

2017 MONTANA CLIMATE ASSESSMENT

Stakeholder driven, science informed

montanaclimate.org

MONTANA INSTITUTE ON ECOSYSTEMS


Bowman Lake, Glacier National Park.
Photograph courtesy of Scott Bischke.

ON THE COVER

Big Hole Valley.
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2017 MONTANA CLIMATE ASSESSMENT

Stakeholder driven, science informed

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Jefferson River at Lewis and Clark Caverns State Park.
Photograph courtesy of Scott Bischke.

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Fort Benton, Montana.
Photograph courtesy of Scott Bischke.

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The line in the middle of the boxplot represents the median value of all model projections. The bottom and top of the box represent the 25th and 75th percentiles (or first and third quartiles), respectively, of model projections. The upper whisker (line extending from the box) extends from the box to the largest model value no further than 1.5*IQR from the box (where IQR is the inter-quartile range, or distance between the first and third quartiles). The lower whisker extends from the box to the smallest model projection that is no further than 1.5*IQR of the hinge. Few model projections fall beyond the end of the whiskers (i.e., outliers), and these are not shown in the figures.

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Hay bales near Whitehall, Montana.
Photograph courtesy of Scott Bischke.

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Marias River.
Photograph courtesy of Scott Bischke.

EXECUTIVE SUMMARY

WHAT IS THE MONTANA CLIMATE ASSESSMENT?

The Montana Climate Assessment (MCA) is an effort to synthesize, evaluate, and share credible and relevant scientific information about climate change in Montana with the citizens of the State. The motivation for the MCA arose from citizens and organizations in Montana who have expressed interest in receiving timely and pertinent information about climate change, including information about historical variability, past trends, and projections of future impacts as they relate to topics of economic concern. This first assessment reports on climate trends and their consequences for three of Montana's vital sectors: water, forests, and agriculture. We consider the MCA to be a sustained effort. We plan to regularly incorporate new scientific information, cover other topics important to the people of Montana, and address the needs of the state.

The process to develop the first MCA was driven by stakeholder input and informed by the best-available science. Insights regarding topics to cover were developed from questionnaires, conversations, and listening sessions held across the state. A team of researchers, educators, and stakeholders used that feedback to select the topics covered.

The Montana Institute on Ecosystems, a statewide center based at both Montana State University and University of Montana, has taken on the responsibility of organizing the MCA. The 2017 MCA is the result of two years of work by university faculty and students, state and federal agency researchers, non-profit organizations, resource managers, and citizens from across Montana.

The assessment begins with an analysis of Montana's recent climate trends and how climate is projected to change in the future (Chapter 2). This information is used throughout the assessment to explain the key impacts of climate change observed in recent decades and projected in the future. Discussion of climate change impacts on Montana's water (Chapter 3), forests (Chapter 4), and agriculture (Chapter 5) are presented next. The assessment concludes with an analysis of major knowledge gaps—and thus areas for future research—related to climate change and its impacts on the three sectors covered herein (Chapter 6).

MONTANA'S CLIMATE

Understanding current climate change and projecting future climate trends is of vital importance, both for our economy and our well-being. The Climate chapter serves as a foundation for the MCA, providing information on present-day climate as well as climate terminology, past climate trends, and future climate projections. The chapter is an introduction to climate science and the important processes that determine whether climate remains constant or changes.

Climate basics

Climate is driven largely by energy from the sun, and the manner in which this incoming solar radiation is reflected, absorbed, transformed (as in photosynthesis), or re-radiated (as heat). Each of these processes influences climate through changes to temperature, the hydrologic cycle, vegetation, and atmospheric and ocean circulation patterns. Climate change, as defined by the US Global Change Research Program (USGCRP undated), includes:

Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system.

Such changes are driven in large part by the greenhouse effect, the trapping of greenhouse gases in Earth's atmosphere and consequent warming of the planet. The rapid rate of climate change since the Industrial Revolution has resulted from changes in atmospheric chemistry, specifically increases in greenhouse gases due to increased combustion of fossil fuels, land-use change (e.g., deforestation), and fertilizer production (Forster et al. 2007). The primary greenhouse gases in the Earth's atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), and ozone (O_3).

Montana's unique features

To understand climate change in Montana, we must first understand Montana's unique geography. Montana is the fourth largest state in the nation and its location within North America exposes the state to a mix of diverse weather systems that originate from the Pacific Ocean, the Arctic, and sometimes subtropical regions. The Continental Divide, which has a predominantly north-south alignment in Montana, effectively splits the state into climatically distinct western wet and eastern dry regions with respect to moisture from eastward-flowing Pacific Maritime air. The state also includes the beginnings of three major river basins—the Missouri, Snake/Columbia, and Saskatchewan—two of which encompass almost one-third of the landmass of the conterminous United States. Consequently, Montana's climate influences the water supply of a large portion of the country, and its water supports communities, ecosystems, and economies far beyond its borders.

Our analysis

Montana's unique geography means that climate varies across the state, as it does across the nation. Throughout the MCA, we aggregate past climate trends and future climate projections into seven Montana climate divisions, as shown in Figure I. These seven climate divisions are a subset of the 344 divisions defined by the National Oceanic and Atmospheric Administration (NOAA) based on a combination of climatic, political, agricultural, and watershed boundaries (NOAA undated).

Montana's Climate Divisions

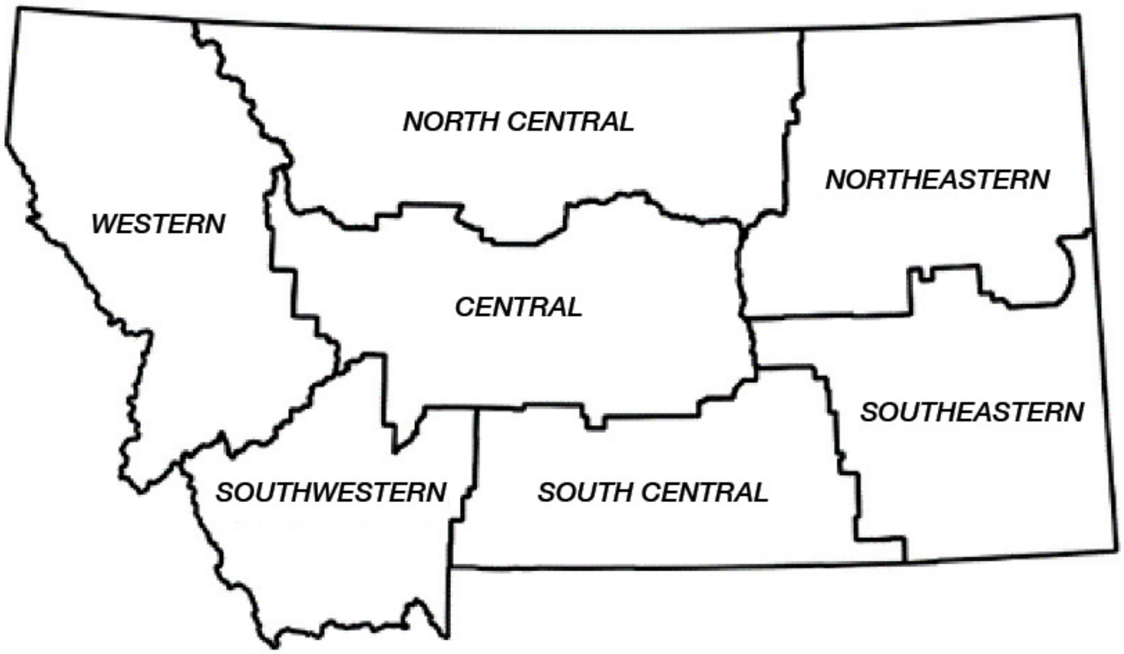

Figure I. Montana's seven climate divisions.

To assess Montana's historical climate, we evaluated temperature and precipitation trends since the mid-20th century by using standard statistical methods to analyze records of temperature and precipitation. To assess future projected changes to Montana's climate, we employed an ensemble of climate models from the fifth iteration of the Coupled Model Intercomparison Project (CMIP5), and utilized a statistically downscaled dataset.

Major findings

The results of this analysis produced several key messages, some of which are shown below, about Montana's historical and future climate (for a complete list of key messages, see the Climate chapter):

- Annual average temperatures, including daily minimums, maximums, and averages, have risen across the state between 1950 and 2015. The increases range between 2.0-3.0°F (1.1-1.7°C) during this period (see Figure II). *[high agreement, robust evidence]* [1]

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[1] Throughout the MCA, we assess our confidence in the key messages by considering a) the level of agreement among experts with relevant knowledge, and b) the quality of the evidence. We use these two factors and the criteria described in the National Climate Assessment to assign the confidence ratings expressed throughout the MCA. See sidebar titled "Expressed Confidence in MCA Key Messages" in the Introduction chapter.

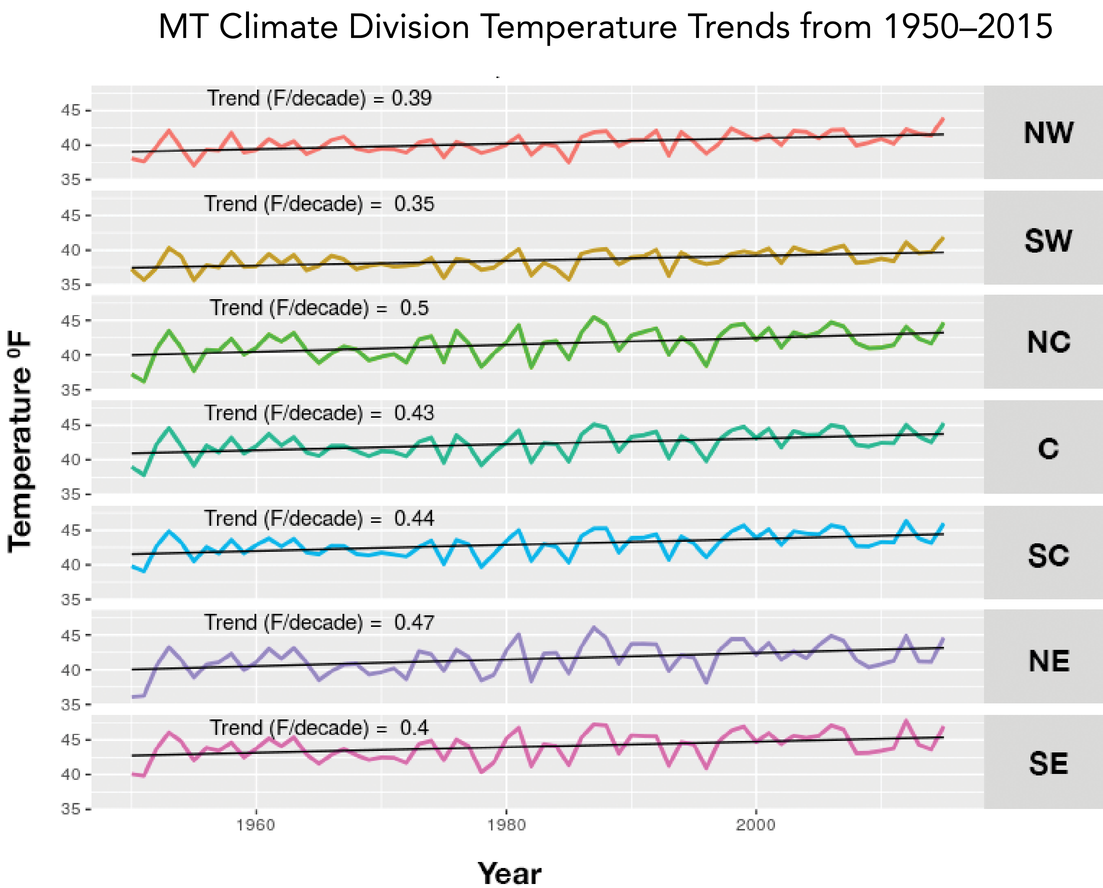

Figure II. Trends in annual average temperature across each climate division (Figure I) in Montana. The divisions are northwestern (NW), southwestern (SW), north central (NC), central (C), south central (SC), northeastern (NE), and southeastern (SE).

- Despite no historical changes in average annual precipitation between 1950 and 2015, there have been changes in average seasonal precipitation over the same period. Average winter precipitation decreased by 0.9 inches (2.3 cm), which can largely be attributed to natural variability and an increase in El Niño events, especially in the western and central parts of the state. A significant increase in spring precipitation (1.3-2.0 inches [3.3-5.1 cm]) also occurred during this period for the eastern part of the state. *[moderate agreement, robust evidence]*
- Montana is projected to continue to warm in all geographic locations, seasons, and under all emission scenarios throughout the 21st century. By mid century, Montana temperatures are projected to increase by approximately 4.5-6.0°F (2.5-3.3°C) depending on the emission scenario. By the end-of-century, Montana temperatures are projected to increase 5.6-9.8°F (3.1-5.4°C) depending on the emission scenario. These state-level changes are larger than the average changes projected globally and nationally (Figure III). *[high agreement, robust evidence]*

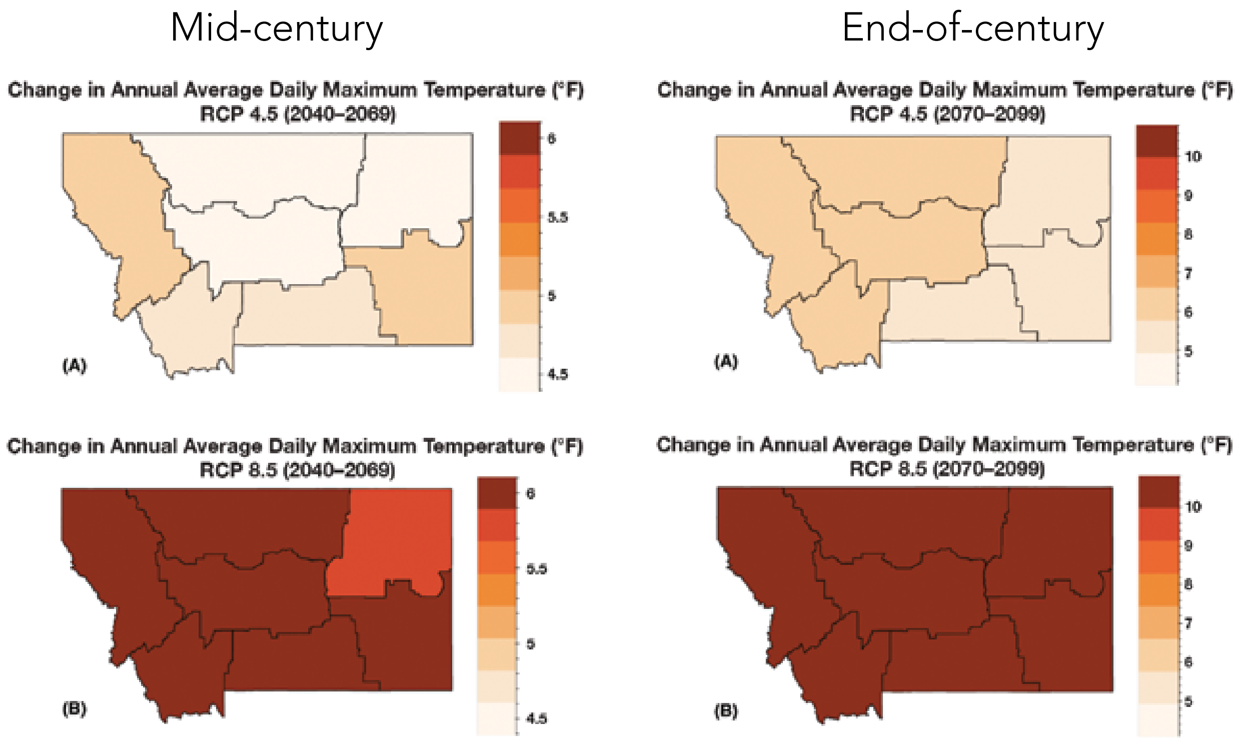

Figure III. The projected increase in annual average daily maximum temperature (°F) for each climate division in Montana for the periods 2049-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

- Across the state, precipitation is projected to increase in winter, spring, and fall; precipitation is projected to decrease in summer. The largest increases are expected to occur during spring in the southern part of the state. The largest decreases are expected to occur during summer in the central and southern parts of the state. *[moderate agreement, moderate evidence]*

Table I provides a summary of climate metrics developed under the MCA.

Table I. Summary of climate metrics.

Climate Metric—	Trend and future scenario
Atmospheric CO_2 concentrations	Global atmospheric carbon dioxide concentrations have increased over 100 ppm since Montana statehood and are projected to increase under both future scenarios considered here.
Average temperature	Since 1950, average statewide temperatures have increased by 0.5°F/decade (0.3°C/decade), with greatest warming in spring; projected to increase by 3-7°F (1.7-3.9°C) by mid century, with greatest warming in summer and winter and in the southeast.
Maximum temperatures	Maximum temperatures have increased most in spring and are projected to increase 3-8°F (1.7-4.4°C) by mid century, with greatest increases in August and in the southeast.
Days above 90°F (32°C)	Extreme heat days are projected to increase by 5-35 additional days by mid century, with greatest increases in the northeast and south.
Minimum temperatures	Minimum temperatures have increased most in winter and spring and are projected to increase 3-7°F (1.7-3.9°C) by mid century, with greatest increases in January and in the southeast.
Frost-free days	Frost-free days are projected to increase by 24-44 days by mid century, particularly in the west.
Average precipitation	Statewide precipitation has decreased in winter (0.14 inches/ decade [-0.36 cm/decade]) since 1950, but no significant change has occurred in annual mean precipitation, probably because of very slight increases in spring and fall precipitation. Precipitation is projected to increase, primarily in spring (0.2-0.7 inches [0.5-1.8 cm]) in the northwest; a slight statewide decrease in summer precipitation and increased year-to-year variability of precipitation are projected, as well.
Number of consecutive dry days	Little projected change, with a maximum increase of 3 days to -3 days under the most severe scenario by end of the century. However, increased variability in precipitation suggests potential for more severe droughts, particularly in connection with climate oscillations.
Number of consecutive wet days	No substantial change projected.

IMPACTS TO MONTANA'S WATER

Water in Montana

Montana depends on an adequate supply of clean water for nearly every aspect of our economy, including food production, hydroelectric power, domestic and industrial uses, and sustaining our natural ecosystems. The vast majority of water that enters Montana comes as rain or snow at higher elevations (MT DNRC 2014a, b, c, d; MT DNRC 2015). Although some of Montana's water originates in Wyoming or adjacent Canadian provinces, over 80% is derived from within state boundaries, hence Montana's designation as a "headwaters state." The major rivers of Montana export more than 40 million acre-feet of water/yr (4.9x1010 m^3/yr)[2] —more than twice the capacity of Flathead Lake—with the majority, approximately 60%, generated in the Clark Fork and Kootenai river basins west of the Continental Divide.

Groundwater is another large and important component of the water cycle in Montana, with most groundwater coming from shallow sand or gravel aquifers in river floodplains. Groundwater resources are critical for water users, but also contribute significantly to natural streamflow throughout the year. In Montana, much of the winter snowfall that accumulates in the mountains melts in spring to produce streamflow and recharge groundwater aquifers. Projected changes in temperature will have large effects on how water enters Montana (e.g., as rain or snow), how it is distributed among major storage pools, and how it moves or changes from one component of the water cycle to another.

Our analysis

To best represent the influence of climate variations on water resources, the Water chapter focuses on eight rivers and their watersheds (Figure IV; note that some watersheds—for example, that of Poplar River—extend beyond the state boundaries). These focal rivers and watersheds, chosen across the state's seven NOAA climate divisions,[3] include:

- Climate division 1
  —Clark Fork River at Saint Regis
  —Middle Fork of the Flathead River at West Glacier
- Climate division 2—Missouri River at Toston
- Climate division 3—Marias River near Shelby
- Climate division 4—Musselshell River at Mosby
- Climate division 5—Yellowstone River at Billings
- Climate division 6—Poplar River near Poplar
- Climate division 7—Powder River near Locate

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[2] 1 acre-foot is 325,851 gal (1233 m^3), enough water to cover an acre of land 1 ft (0.3 m) deep.

[3] For more detail on our focal rivers and watersheds see Appendix 3-1 on the MCA website.

Selected Focal Watersheds

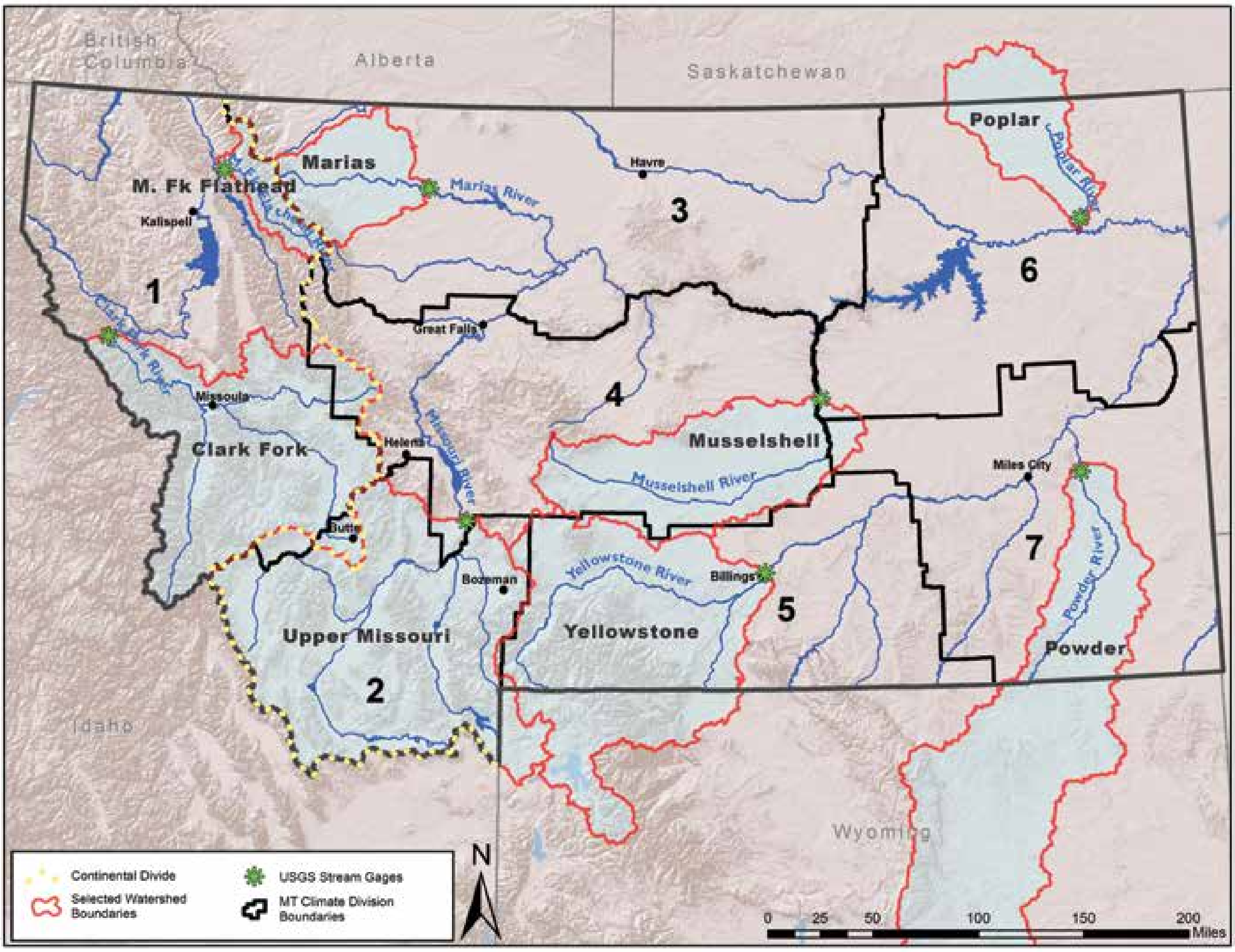

Figure IV. The focal rivers for this assessment, including black outlines of the seven climate divisions (see Water chapter), contributing watersheds (red), river gage locations (green), and the Continental Divide (dotted).

Complex computer models (see Climate chapter) provide a method for projecting future climate scenarios in Montana. By linking climate models to water-cycle models, we generate projections about how climate change is likely to influence water resources. For the projections in the Water chapter, we present results from as many as 31 climate models that are linked to a water-cycle model. We utilize these projections to discuss how climate change may affect key components of the water cycle, including:

- Snowpack
- Snowmelt runoff and timing
- Annual streamflow
- Groundwater resources
- Drought

Major findings

The results of this analysis produced several key messages, some of which are shown below, about how climate change will affect Montana's water resources (for a complete list of key messages, see the Water chapter).

Rising temperatures will reduce snowpack, shift historical patterns of streamflow in Montana, and likely result in additional stress on Montana's water supply, particularly during summer and early fall. Key messages associated with these findings follow:

- Montana's snowpack has declined over the observational record (i.e., since the 1930s) in mountains west and east of the Continental Divide; this decline has been most pronounced since the 1980s. *[high agreement, medium evidence]*

- Warming temperatures over the next century, especially during spring, are likely to reduce snowpack at mid and low elevations. *[high agreement, robust evidence]*

- Historical observations show a shift toward earlier snowmelt and an earlier peak in spring runoff in the Mountain West (including Montana). Projections suggest that these patterns are very likely to continue into the future as temperatures increase. *[high agreement, robust evidence]*

- Earlier onset of snowmelt and spring runoff will reduce late-summer water availability in snowmelt-dominated watersheds. *[high agreement, robust evidence]*

- Groundwater demand will likely increase as elevated temperatures and changing seasonal availability of traditional surface-water sources (e.g., dry stock water ponds or inability of canal systems to deliver water in a timely manner) force water users to seek alternatives. *[high agreement, medium evidence]*

Rising temperatures will exacerbate persistent drought periods that are a natural part of Montana's climate. Key messages associated with these findings follow:

- Multi-year and decadal-scale droughts have been, and will continue to be, a natural feature of Montana's climate *[high agreement, robust evidence]*; rising temperatures will likely exacerbate drought when and where it occurs. *[high agreement, medium evidence]*

- Changes in snowpack and runoff timing will likely increase the frequency and duration of drought during late summer and early fall. *[high agreement, medium evidence]*

IMPACTS TO MONTANA'S FORESTS

Forests in Montana

In the Forest chapter, we interpret how past and projected changes in climate—as described in the Climate chapter—may influence Montana forests. There are approximately 23 million acres (9.3 million ha) of forested land in Montana, and most are publicly owned, in the western part of the state and dominated by Douglas-fir, lodgepole pine, and ponderosa pine (Figure V). Forest conditions in Montana are varied, and potential impacts from climate change will overlay on existing stresses to forests. Ultimately, forest managers will need to consider specific adaptation actions in response to current and potential climate changes.

Existing Forest Cover Type in Montana

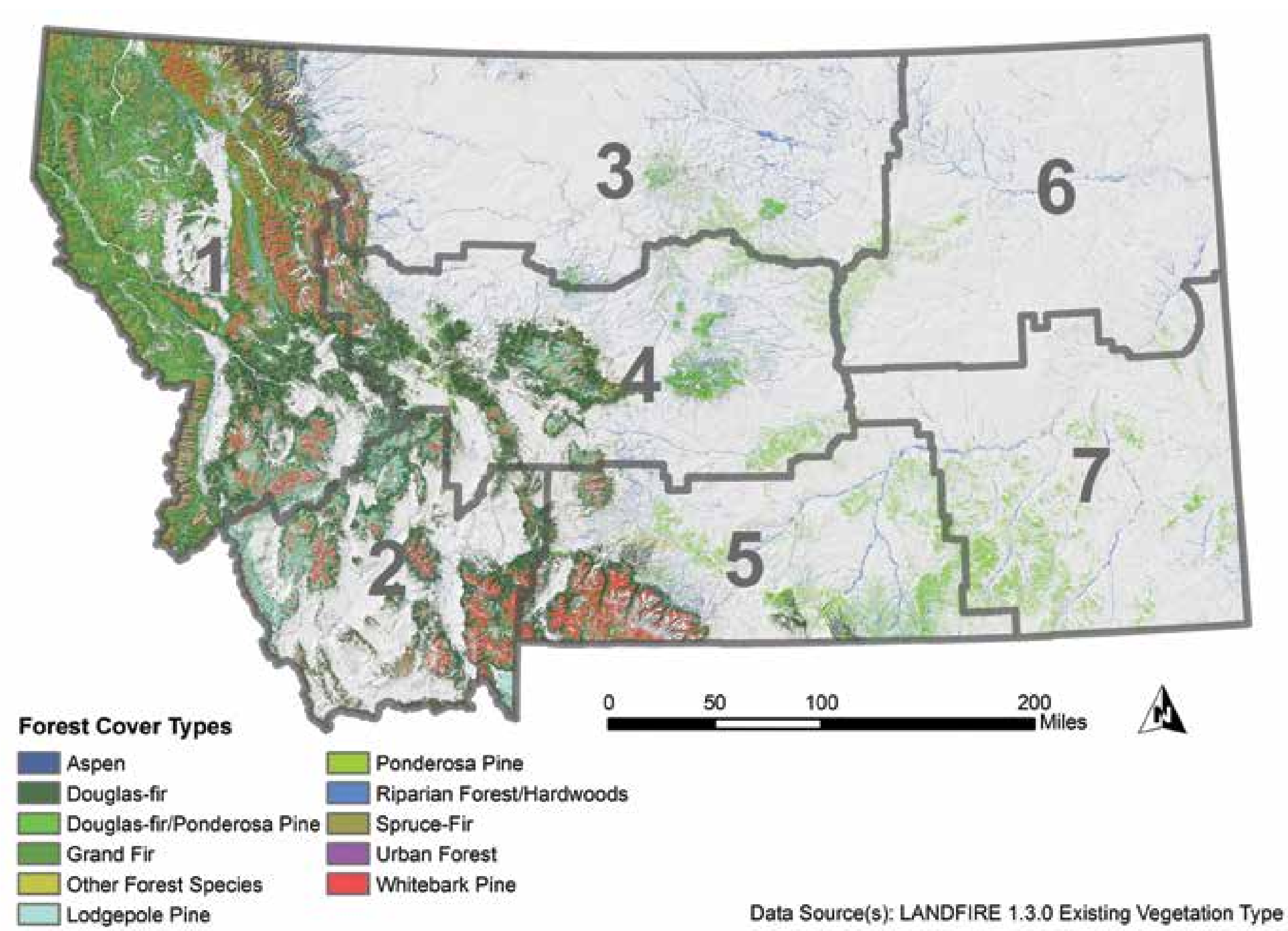

Figure V. Existing forest cover type in Montana (Landfire 2012). Gray boundaries delineate climate divisions (see Figure I).

Our analysis

In the face of changing climate, forest managers can best maintain forest health and stable product yield by understanding past trends and planning for a range of climate scenarios. The analysis in the Forest chapter is based on the climate trends for which we had sufficient data and climate projections that represent plausible future scenarios, as described in the Climate chapter. It is important to note that current forest conditions will largely determine the potential impacts from current and future climate change. Forest conditions vary across land ownership types, and many Montana forests are under stress due to past forest management practices. In addition, we do not detail potential responses of individual tree species to climate shifts in this assessment; instead, we focus on the direct and indirect effects of climate change on forests. We point the reader to Chapter 6 in the Northern Region Assessment Program report (Keane et al. forthcoming) for species-level information.

Major findings

The direct effects of climate change on forests include increased temperatures and shifts in precipitation that together alter humidity, soil moisture, and water stress. Direct effects can be beneficial or detrimental to forest growth and survival. The results of this analysis on the direct effects of climate change on Montana's forests produced several key messages, some of which are shown below (for a complete list of key messages, see the Forests chapter):

- Increased temperatures will have positive or negative effects on individual trees and forest-wide processes, depending on local site and stand conditions, but impacts from increased extreme heat will be negative. *[high agreement, moderate evidence]*
- Direct effects of climate change on individual trees will be driven by temperature in energy-limited forests and moisture in water-limited forests. *[high agreement, moderate evidence]*
- The speed and magnitude of climate change may mean that increased forest mortality and contractions in forest distribution will outpace any gains in forest growth and productivity over the long run, leading to a net loss of forested area in Montana. *[medium agreement, limited evidence]*

Table II provides a summary of potential climate-related direct effects to forests.

Table II. Summary of potential climate-related direct effects to forests.

Direct effect	Possible impacts	Projected net effect
Establishment and regeneration	**Positive:** Higher CO_2 concentrations and temperatures may lead to increased tree fecundity **Negative:** Higher temperatures and reduced water availability could reduce seedling survival	Possible positive or negative effects are superimposed on climate oscillations, such as the Pacific Decadal Oscillation, which can produce decades of cooler and wetter conditions that may be more favorable for establishment and regeneration
Growth and productivity	**Positive:** Increased vegetation water use and increased growth and productivity as a result of longer growing season **Negative:** Reduced growth and productivity in water limited areas	Possible increased growth and productivity concurrent with climate oscillations that increase water availability, particularly at higher elevations and where stand density is low; extreme high temperatures would have net negative impact, regardless of water availability
Mortality	**Positive:** Few opportunities for reduced direct climate effects on mortality but possibility for reduced mortality from indirect effects **Negative:** Increased acute and background mortality from increased temperatures and indirectly from increased disturbance	Increased mortality, although may be driven by indirect effects; patterns of mortality will be dependent on initial stand and local site conditions, but more arid regions more susceptible
Range shifts and forest distribution	**Positive:** Potential range expansion with warmer temperatures and sufficient moisture **Negative:** Potential range contraction where temperature is too high or in water-limited locations	Possible faster range contraction compared to expansion, with net range reduction particularly in drier areas; no clear direction of elevational shifts; responses will be highly species and location dependent

Indirect effects of climate change on forests include disturbance—a key component of forest ecology—and may be more important, immediate, and longer lasting than direct effects. As with direct effects, indirect effects can compound existing forest conditions and impacts from past and future human land-use activities (Moritz and Agudo 2013).

The results of this analysis on the indirect effects of climate change on Montana's forests produced several key messages, some of which are shown below (for a complete list of key messages, see the Forests chapter):

- An increase in fire risk (i.e., probability of occurrence)—including an increase in size and possible frequency and/or severity (i.e., tree mortality)—is expected in the coming century as a result of a) prolonged fire seasons due to increased temperatures, and b) increased fuel loads from past fire suppression. *[high agreement, robust evidence]*

- Rising temperatures are likely to increase bark beetle survival [high agreement, strong evidence], but climate-induced changes to other insects and forest pathogens are more varied and less certain *[medium agreement, moderate evidence]*

- There may be a reduction in the amount of carbon stored in forests. *[low agreement, limited evidence]*

Table III provides a summary of potential climate-related indirect effects to forests.

Table III. Summary of potential climate-related indirect effects to forests.

Indirect effect	Possible impacts	Projected net effect
Disturbance: fire	**Positive:** Increased forest heterogeneity (long-term, post-burn) **Negative:** Decreased forest diversity and heterogeneity (immediately post-burn); increased social and economic impacts from fire; increased release of forest carbon	Increased fire severity resulting primarily from warmer weather and past fire suppression; increased release of forest carbon from fire
Disturbance: pathogens	**Positive:** Some pathogen species may decline and result in decreased forest mortality **Negative:** Some pathogens species may increase and result in increased forest mortality and increased susceptibility to beetle attack	Uncertain climate effects on pathogens, dependent on moisture regimes, pathogen species, and host species
Disturbance: insects	**Negative:** Increased forest mortality; reduced forest diversity with shift towards non-host tree species	Increased temperatures likely to result in increased insect disturbance, but dependent on elevation, insect species and host availability
Soil responses and carbon storage	**Positive:** Increased organic matter if increased productivity; increased nitrogen availability **Negative:** Decreased organic matter (with increased decomposition rates); decreased mycorrhizal support; increased soil acidity; increased release, or decreased removal, of atmospheric CO_2	Uncertain climate effects on soil responses, but projected reductions in soil and forest carbon storage

IMPACTS TO MONTANA'S AGRICULTURE

Agriculture in Montana

Agriculture is a key industry in Montana, generating over $5.2 billion in 2014 through the sale of agricultural commodities (USDA-NASS 2015). Montana's large agricultural industry consists of both crops and livestock. Montana's farm and ranchland support a mosaic of dryland and irrigated agriculture, commodity and specialty cropland, and native and planted rangeland. Although more Montanans live in cities than on farms and ranches, we think of Montana as an agricultural state, where the non-forested landscape is dominated by livestock and crop production.

Our analysis

Montana agriculture has always faced volatility, extreme events, and variability across the state and these conditions will continue to be the case with projected climate changes in Montana. Climate model projections show a warmer Montana in the future, with mixed changes in precipitation, more extreme events, and mixed certainty about upcoming drought. The Agriculture chapter examines potential impacts of projected climate change on commodity crops, livestock, pollinators, disease, pests, and weeds. However, any effort at assessing climate impacts on agriculture faces multiple levels of uncertainty, including uncertainty that a) accompanies all climate projections, b) is specific to agricultural projections, and c) is created by adaptive actions (human interventions) that can mask a direct climate signal. Climate impacts on agriculture in other regions of the world can also create uncertainty and have a major impact on Montana agriculture by changing commodity prices and input costs. Increasing uncertainty due to complex interactions, whether through volatility or new and hard-to-predict temperature and moisture trends, can disrupt agricultural decision-making and will probably become an even more important direct agriculture decision-driver in the years ahead (See Figure VI).

Major findings

The results of this analysis produced several key messages, some of which are shown below, about how climate change will affect Montana agriculture (for a complete list of key messages, see the Agriculture chapter):

Factors that Drive Agricultural Decisions in Montana

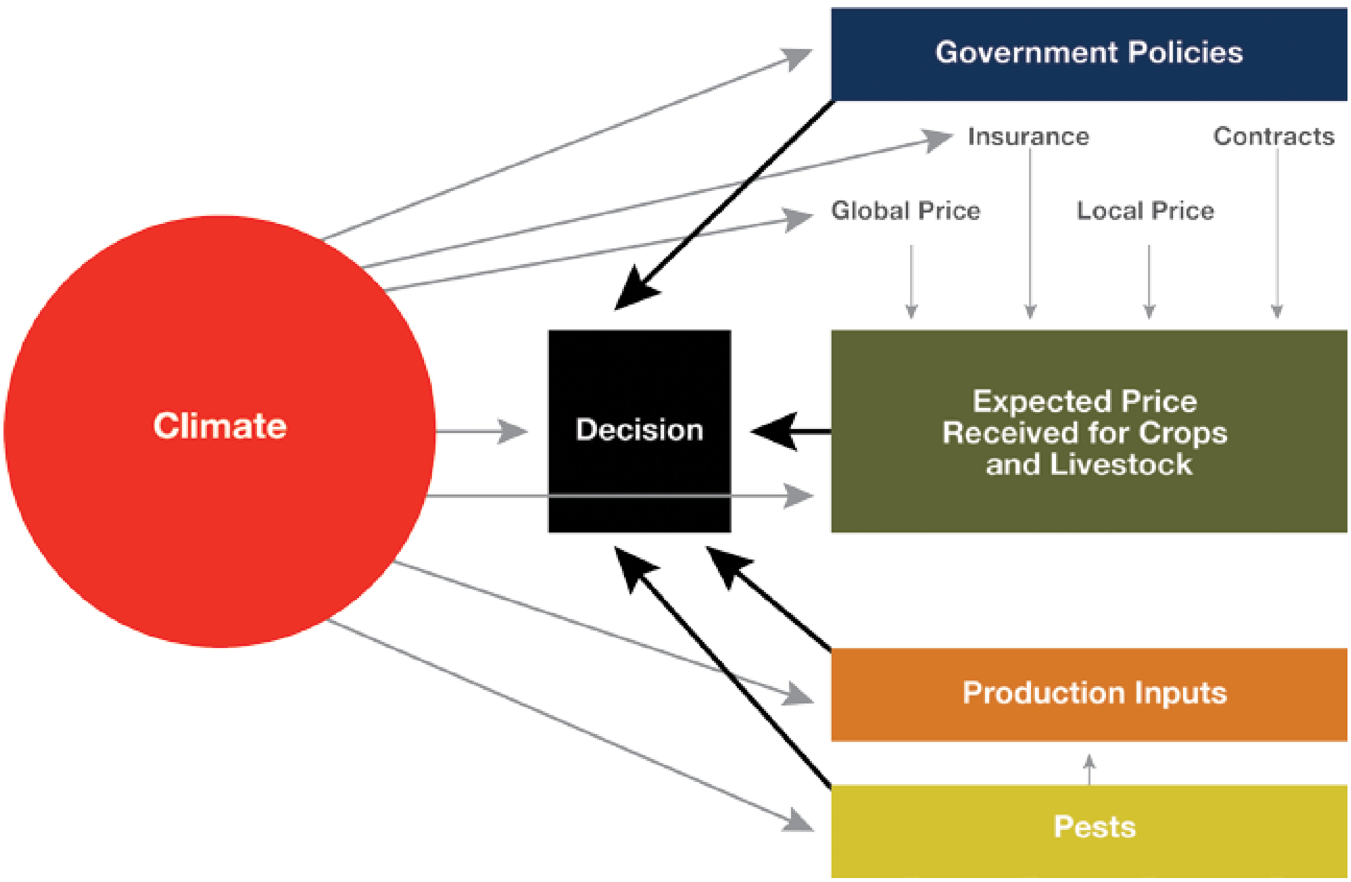

Figure VI. Factors that drive agricultural decisions in Montana. The size of bubble and arrows qualitatively represents the relative importance of each factor's influence on agricultural production decisions.

- Every component of agriculture—from prices to plant pollinators and crop pests—exhibits complex relationships to climate, depending on the location, weather variability, and agricultural and economic practices and policies (Figure VI). Social and economic resilience to withstand and adapt to variable conditions has always been a hallmark of Montana farmers' and livestock producers' strategies for coping with climate variability. *[high agreement, robust evidence]*

- Decreasing mountain snowpack will continue to lead to decreased streamflow and less reliable irrigation capacity during the late growing season. Reduced irrigation capacity will have the greatest impact on hay, sugar beet, malt barley, market garden, and potato production across the state. *[high agreement, robust evidence]*

- Increases in temperature will allow winter annual weeds, such as cheatgrass, to increase in distribution and frequency in winter wheat cropland and rangeland. Their spread will result in decreased crop yields and forage productivity as well as increased rangeland wildfire frequency. *[high agreement, medium evidence]*

- Climate change affects global-price-determined commodity agriculture differently than it affects non-commodity agriculture. Commodity crops, such as small grains, are more directly driven by global markets and agricultural subsidies, whereas non-commodity crops tend to be more directly tied to local or specialized non-local markets and local micro-climates. *[high agreement, medium evidence]*

- Diversified cropping systems, including rotation with pulse crops and innovations in tillage and cover-cropping, along with other measures to improve soil health, will continue to allow adaptation to climate change. *[medium agreement, low evidence]*

CONCLUSIONS

The 2017 Montana Climate Assessment focused on three sectors that Montana stakeholders identified as important to their lives: water, forests, and agriculture. The MCA found that all three of these sectors have experienced impacts from climate change over the last half century. In addition to exploring how the past climate has changed and its effects on Montana, the MCA explored how future projected climate change would also affect water, forests, and agriculture across the state. The overall objective of the MCA is to inform Montanans about the state's changing climate so that they can better plan for the future.

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Bridger Range fall sunset.
Photograph courtesy of Scott Bischke.

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Madison Valley, looking toward the Madison Range.
Photograph courtesy of Scott Bischke.

LIST OF ACRONYMS

CMIP—Coupled Model Intercomparison Project

DNRC—Department of Natural Resources and Conservation (State of Montana)

IPCC—Intergovernmental Panel on Climate Change

MCA—Montana Climate Assessment

NAS—National Academy of Sciences

NASS—National Agriculture Statistics Service

NASA—National Aeronautics and Space Administration

NCA—National Climate Assessment

NOAA—National Oceanic and Atmospheric Administration

NRCS—Natural Resources Conservation Service

RCP—Representative Concentration Pathways
SNOTEL—SNOwpack TELemetry

SWE—snow water equivalent

USDA—United States Department of Agriculture

USGCRP— United States Global Change Research Program

USGS—United States Geological Survey

WSS—wheat stem sawfly

FOREWORD

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1 September 2017

The most recent National Climate Assessment was released in 2014 as part of a mandate from the United States Congress to report on the impacts of climate change now and in the future. That assessment covered many sectors and regions in an effort to summarize the impacts of climate change on the entire nation. Given the broad mandate of the assessment, it was not possible to focus on any one state. For example, in the National Climate Assessment, Montana is included in the Great Plains region, which covers a vast expanse from the Canadian border down to Texas and overlooks the diverse geography of Montana that ranges from snow-capped forested peaks to dry prairies. So, while the National Assessment is useful for understanding climate change at continental and regional scales, it is less clear how the information can be utilized at the local level. Thus, scientists and stakeholders in Montana were motivated to pursue a state-level effort to address the information needs of people making on-the-ground decisions. Hence, this first Montana Climate Assessment (MCA).

The 2017 MCA represents a grand experiment in science-stakeholder engagement. The objective has been to achieve a product that is scientifically accurate, up-to-date, and specific enough to serve the needs of local communities. From the outset, the MCA has purposefully engaged state-

Rocky Mountain Front.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

and local-level stakeholders in the development of the assessment in order to be most responsive to their needs. Additionally, as in the national level assessment, the MCA is committed to providing a synthesis and assessment of the best available science. The MCA synthesizes a large body of climate change literature, which is often technical, complex, and hard to interpret by a layperson. The primary goal of this assessment has been to translate these findings and explain their implications at a local and state level.

Importantly, in addition to its science focus, the MCA incorporates the practical knowledge and experience of indigenous groups, as well as agriculture and forestry practitioners in Montana and beyond.

To ensure that the objectives of transparency, relevance, and usefulness were met with the first MCA, the assessment underwent rigorous review before publication. The scientific content of the MCA was extensively reviewed at the highest level by experts to ensure its accuracy. Furthermore, public comment was solicited from over 1500 stakeholders directly and the general public at large.

I believe the Montana Climate Assessment is a model for how state assessments can be developed and provides an example of how to connect climate change information at the national and international levels to the challenges faced at the local scale. The MCA illustrates the importance of public universities to provide objective information that can help educate the public and inform decision makers at all levels. It also shows the benefits of broad collaboration, participation, and new partnerships.

Along with being a stand-alone report, the MCA is provided as an interactive web report to help it reach as many stakeholders as possible and to allow for rapid update as new information becomes available. As of its release, this first MCA is the best source of information about climate change in Montana. I commend it to your study and use.

01. INTRODUCTION TO THE MONTANA CLIMATE ASSESSMENT

Cathy Whitlock

The Constitution of the State of Montana, ratified in 1972, affirms Montanans' inalienable "right to a clean and healthful environment" (State of Montana 1972). Since the signing of the constitution, that declaration has galvanized Montanans to protect the state's air and water, and to work toward keeping the state free from toxic pollutants. Today, that declaration also means living safely, successfully, and with foresight in a world undergoing climate change.

The right to a clean and healthful environment, including issues around climate change, requires that Montanans have access to the best and most relevant scientific information, updated at regular intervals, and consider new discoveries as they become available. The information behind the Montana Climate Assessment reflects decades of peer-reviewed research from Montana's universities and agencies, new analyses by chapter authors, as well as the insights and observations of resource managers, farmers, tribal community members, and other citizens from across the state. It also builds on research undertaken across the country and around the world. At the end of the day, it is important to understand what climate change means for Montanans now, and how current information will help us make wise decisions for future generations.

Montanans' Right to a Clean, Healthful Environment

The Constitution of the State of Montana affirms Montanans' inalienable "right to a clean and healthful environment." Today, that declaration includes Montanans having the ability to live safely, successfully, and with foresight in a world undergoing climate change.

Montana's landscapes are vast and diverse. They range from the alpine and forested ecosystems of the Northern Rockies to the parklands and grasslands of central and eastern Montana. Our snow-capped peaks and glaciers are headwaters to three of the major river systems in North America: the Missouri, Snake/Columbia, and Saskatchewan. Montana's climate is as diverse as any state in the nation, shaped by the interaction of air masses from the Pacific, the Arctic, and the Gulf of Mexico, and by storm systems as they move across the state. As a result of this complex interaction of weather and topography, the climate and day-to-day weather are highly variable across the state, from western Montana to the Rocky Mountain Front, the Yellowstone River basin, and the High Plains.

Despite its variability, Montana's climate is critical to our economy, which is in large part based on natural and managed resources. Climate influences the state's water supply and the economies that water supports (and, as Montana is a headwaters state, the economies of much of the nation). Montana includes over 23 million acres (9.3 million hectares) of forested land that is both publicly and privately owned, and is also a major agricultural state with billions of dollars in commodity sales annually. Further, in places where tourism and recreation are economically important, climate influences Montana's snowpack, pristine streams, native forests, and iconic wildlife, which are important for sustained prosperity. In still other parts of Montana, climate variations and weather events directly affect livelihoods in isolated rural communities with limited access to services. Stated simply, the prosperity of Montanans is strongly dependent on the current climate and its stability.

Climate conditions are inherently dynamic, changing at home and around the world. Human-caused climate change has the potential to change these dynamics in unpredictable ways, and no part of the planet will be untouched by these changes. At a global scale, the international scientific community has indicated that average annual temperature will at least be 2.5°F (1.4°C) and likely 3.6°F (2.0 °C) higher in the next century than it was between 1850-1950, with ensuing consequences for both human health and livelihoods (IPCC 2013). Current trends and projected climate changes in Montana are consistent with global patterns (Figure 1-1). The state's temperature has increased 2-3°F (1.1-1.7°C) in the last 65 yr (1950-2015), and climate models project as much as a 9.8°F (5.4°C) warming across the state by the end of the century.

Global Climate Projections

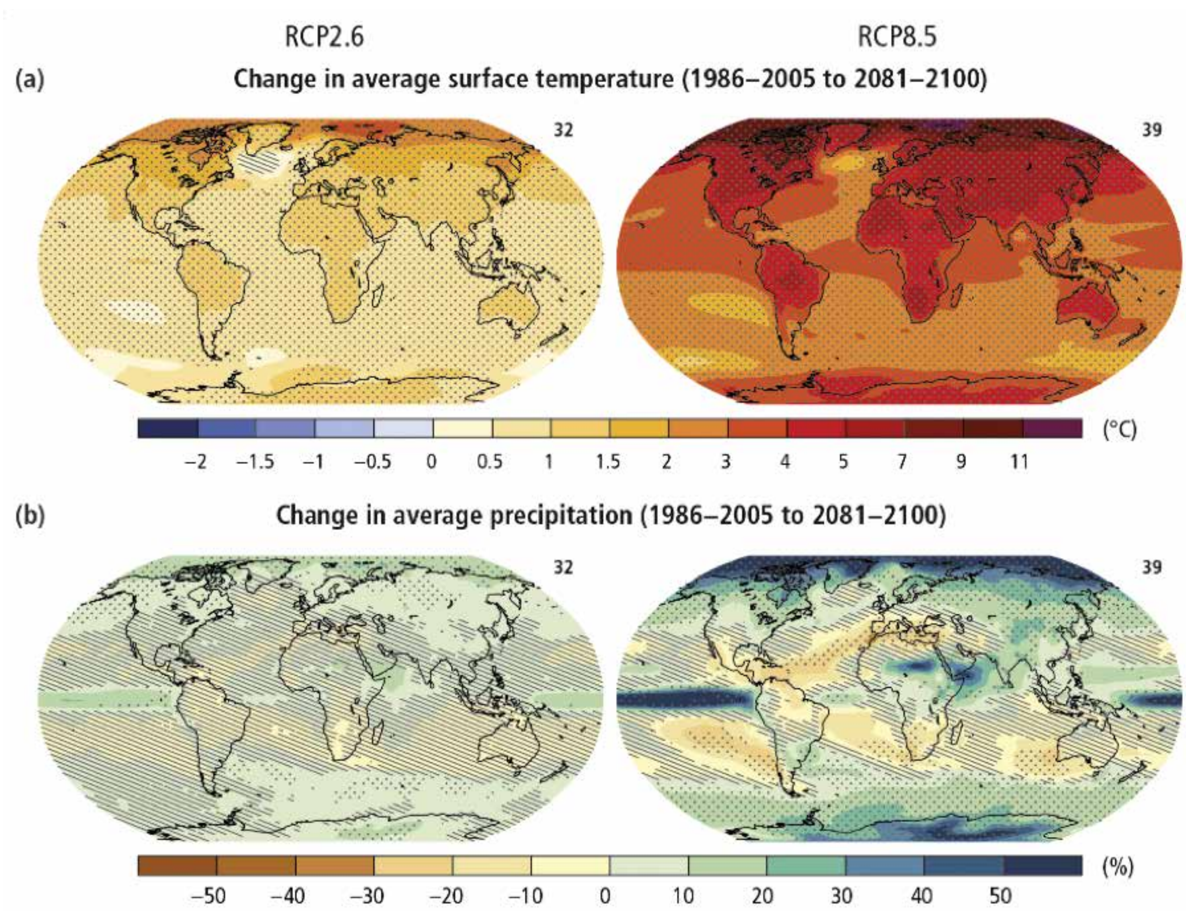

Figure 1-1. Global climate projections from the Intergovernmental Panel on Climate Change, showing temperature and precipitation trends for two different future scenarios, as described in the Climate chapter of this assessment (IPCC 2014a).

With such changes on the horizon, timely information is clearly needed. Scientific assessments are essential tools for linking knowledge to decision-making, by surveying and synthesizing peer-reviewed scientific information across disciplines, sectors, and regions. Assessments highlight key information that can improve understanding of complex issues and identify significant knowledge gaps where more information is needed. An assessment of Montana's changing climate and its resultant effects helps bring scientifically based information to the people of our state in an organized and understandable manner.

The 2017 Montana Climate Assessment (MCA) is the second effort to present the science of climate change at a level that is useful for our state.[4] The Montana Institute on Ecosystems, a statewide center based at both Montana State University and University of Montana, has taken on the responsibility of organizing the MCA. The MCA is the result of two years of effort by university faculty and students, state and federal agency researchers, non-profit organizations, resource managers, and citizens from across Montana. Through questionnaires and listening sessions, Montana stakeholders helped identify what climate changes are of greatest concern to Montanans, what types of climate-change information are most needed, and what mechanisms are most helpful in delivering information. Leading climate scientists at the regional and national level provided independent review of the findings of this assessment to ensure its credibility. Public comment was also solicited and considered. The audience for this assessment includes natural and cultural resource managers, policy makers, state and federal government agencies, and local businesses and communities, as well as the public at large.

This assessment is intended to be the first of a sustained effort, one that will be updated and expanded on a regular basis. In this way, the MCA contributes to the flow of information from the national level to the regional, state, and local levels. It is intended to help decision makers weigh different strategies for responding to climate change effects and incorporate new knowledge as it becomes available. The MCA also attempts to engender information flow in the opposite direction—by encouraging decision makers to identify critical information gaps that require new scientific investigation, tool development, and future assessment.

The Montana Climate Assessment begins with an analysis of Montana's climate trends and how climate is projected to change in the future (Chapter 2). This information is used throughout the assessment to explain the key impacts that climate change may or will produce in Montana. This assessment is focused on the analysis of climate change impacts to the sectors of water (Chapter 3), forests (Chapter 4), and agriculture (Chapter 5). The assessment concludes with an analysis of the major information gaps—and thus areas for future research—related to climate change and its impacts to the three sectors covered herein (Chapter 6).

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[4] The first effort was the Montana Climate Change Action Plan in 2007, created by the Governor's Climate Change Advisory Committee (2007).

Each chapter presents a set of key messages that are used to organize the information and familiarize the reader with the most important findings of the assessment. For each key message, we provide a statement of confidence in our findings. We categorically rated the certainty of key messages on the basis of evidence and agreement, following the approach used by the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (see sidebar) (IPCC 2014b). For each key message, the authors of the relevant chapter rated evidence as "limited," "medium," or "robust" depending on the type, amount, and quality of the scientific evidence supporting the message. Authors also rated the agreement—the consistency of the evidence among scientific reports—as "low," "medium," or "high." The authors offer their expert judgement in these relative assessments of evidence and agreement, and provide details in the text to support their ratings. The greater the evidence and agreement, the higher the level of confidence the authors have in the certainty of the key message.

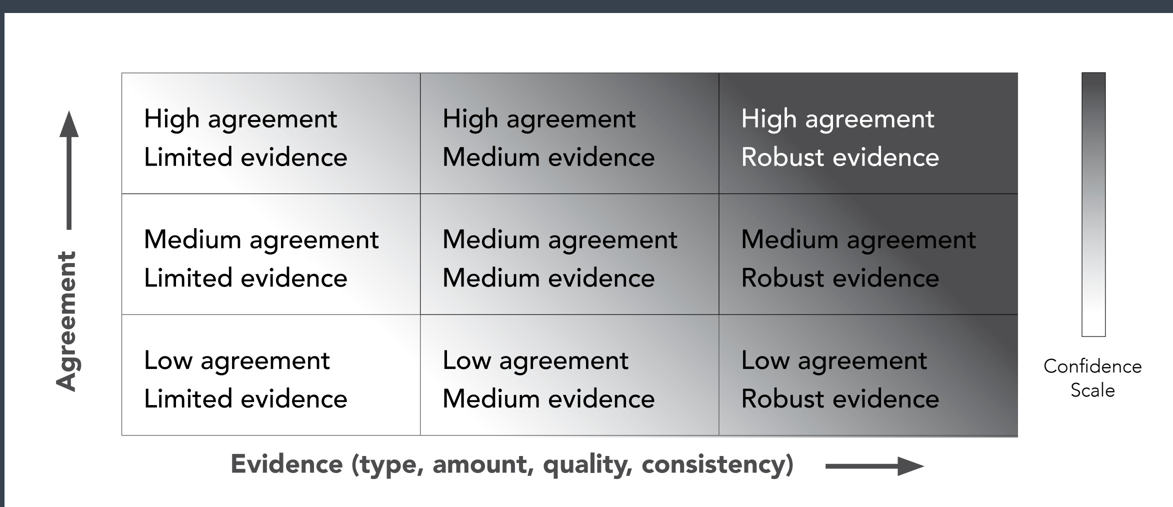
From these key messages and supporting assessment content, it is clear that climate is changing and there are measureable effects on production systems and ecosystems in Montana. There is strong evidence that both temperatures and precipitation will increase in the future. These climate changes have measurable effects, like reductions in ground and surface water resources due to changing timing of precipitation and snowmelt, and measurable impacts like declining forest health and more wildfires, to altered crop seasons and greater irrigation demand.

An increased awareness and understanding of changing patterns, effects, and impacts in Montana, now and into the future, will help our state plan, make decisions, and take actions to promote the good health and prosperity of the people and landscapes of Montana. The MCA provides additional understanding of these changes within the state of Montana and suggests some guidance for strategies and options to respond to their impacts. We hope that this first Montana Climate Assessment motivates much-needed discussion that considers multiple sources of knowledge, and that it leads to science-informed planning efforts and action in the areas of water, forests, and agriculture, as well as sets a pathway for future climate-change research relevant to Montana.

Expressed Confidence in MCA Key Messages

For the assessments of climate impacts made herein, we follow guidance from the National Climate Assessment and Intergovernmental Panel on Climate Change (IPCC) on how to standardize confidence levels and uncertainty characterization in our key messages, as provided below.

Each key message provided in the Montana Climate Assessment is followed by a parenthetical expression of confidence. We asked our authors to assess their confidence in the key message by considering a) the quality of the evidence and b) the level of agreement among experts with relevant knowledge used to craft the message. We then used these two factors and the criteria used in the National Climate Assessment (see graphic below) to assign the confidence ratings expressed in the MCA.



A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases towards the top-right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence (figure and caption text from IPCC Fifth Assessment Report [modified from IPCC 2014b]).

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Little Rockies storm.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

02. CLIMATE CHANGE IN MONTANA

Nick Silverman, Kelsey Jencso, Paul Herendeen, Alisa Royem, Mike Sweet, and Colin Brust

Understanding current climate change and projecting future climate trends are of vital importance–both for our economy and our well-being. It is our goal to provide science-based information that serves as a resource for Montanans who are interested in understanding Montana's climate and its impacts on water, agricultural lands and forests. To provide this understanding, we can learn from past climate trends. However, knowledge of the past is only partially sufficient in preparing for a future defined by unprecedented levels of greenhouse gases in the atmosphere. Therefore, we also provide projections of change into the future using today's best scientific information and modeling techniques.

KEY MESSAGES

- Annual average temperatures, including daily minimums, maximums, and averages, have risen across the state between 1950 and 2015. The increases range between 2.0-3.0°F (1.1-1.7°C) during this period. *[high agreement, robust evidence]*

- Winter and spring in Montana have experienced the most warming. Average temperatures during these seasons have risen by 3.9°F (2.2°C) between 1950 and 2015. *[high agreement, robust evidence]*

- Montana's growing season length is increasing due to the earlier onset of spring and more extended summers; we are also experiencing more warm days and fewer cool nights. From 1951-2010, the growing season increased by 12 days. In addition, the annual number of warm days has increased by 2.0% and the annual number of cool nights has decreased by 4.6% over this period. *[high agreement, robust evidence]*

- Despite no historical changes in average annual precipitation between 1950 and 2015, there have been changes in average seasonal precipitation over the same period. Average winter precipitation has decreased by 0.9 inches (2.3 cm), which can mostly be attributed to natural variability and an increase in El Niño events, especially in the western and central parts of the state. A significant increase in spring precipitation (1.3-2.0 inches [3.3-5.1 cm]) has also occurred during this period for the eastern portion of the state. *[moderate agreement, robust evidence]*

- The state of Montana is projected to continue to warm in all geographic locations, seasons, and under all emission scenarios throughout the 21st century. By mid century, Montana temperatures are projected to increase by approximately 4.5-6.0°F (2.5-3.3°C) depending on the emission scenario. By the end-of-century, Montana temperatures are projected to increase 5.6-9.8°F (3.1-5.4°C) depending on the emission scenario. These state-level changes are larger than the average changes projected globally and nationally. *[high agreement, robust evidence]*

- The number of days in a year when daily temperature exceeds 90°F (32°C) and the number of frost-free days are expected to increase across the state and in both emission scenarios studied. Increases in the number of days above 90°F (32°C) are expected to be greatest in the eastern part of the state. Increases in the number of frost-free days are expected to be greatest in the western part of the state. *[high agreement, robust evidence]*

- Across the state, precipitation is projected to increase in winter, spring, and fall; precipitation is projected to decrease in summer. The largest increases are expected to occur during spring in the southern part of the state. The largest decreases are expected to occur during summer in the central and southern parts of the state. *[moderate agreement, moderate evidence]*

Climate Change Defined

The US Global Change Research Program (USGCRP undated) defines climate change as follows: "Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system."

This chapter focuses on three areas:

1 providing a baseline summary of climate and climate change for Montana—with a focus on changes in temperature, precipitation, and extreme events—including reviewing the fundamentals of climate change science;

2 reviewing historical trends in Montana's climate, and what those trends reveal about how our climate has changed in the past century, changes that are potentially attributable to world-wide increases in greenhouse gases; and

3 considering what today's best available climate models project regarding Montana's future, and how certain we can be in those projections.

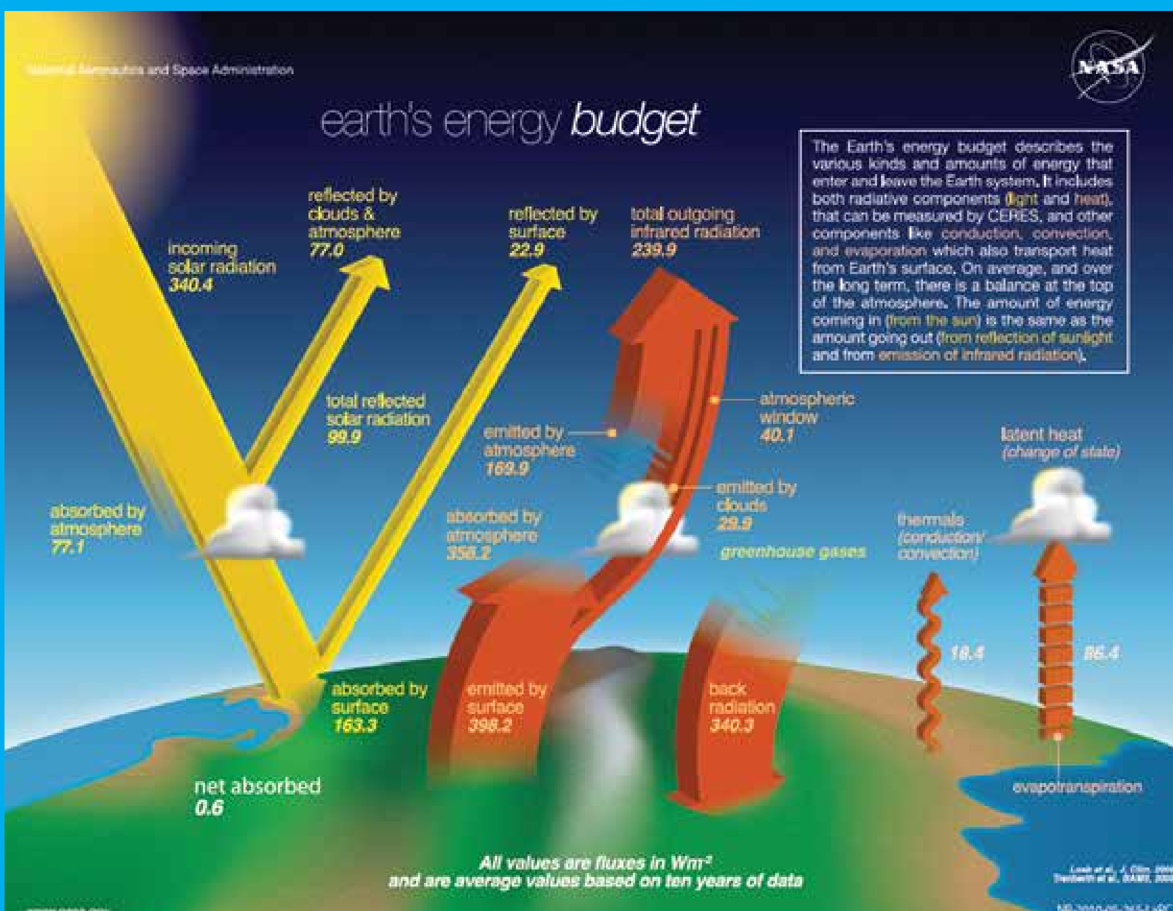
This chapter serves as a foundation for the Montana Climate Assessment, providing information on present-day climate and climate terminology, past climate trends, and future climate projections. This foundation then serves as the basis for analyzing three key sectors of Montana—water, forests, and agriculture—considered in the other chapters of this assessment. In the sections below, we introduce the climate science and discuss important fundamental processes that determine whether climate remains constant or changes.

NATURAL AND HUMAN CAUSES OF CLIMATE CHANGE

Climate is driven largely by radiation from the sun. Incoming solar radiation may be reflected, absorbed by land surface and water bodies, transformed (as in photosynthesis), or emitted from the land surface as longwave radiation. Each of these processes influences climate through changes to temperature, winds, the water cycle, and more. The overall process is best understood by considering the Earth's energy budget (see sidebar).

The Earth's Energy Budget

The Earth's climate is driven by the sun. The balance between incoming and outgoing radiation—Earth's radiation or energy budget—determines the energy available for changes in temperature, precipitation, and winds and, hence, influences atmospheric chemistry and the hydrologic cycle. The Earth's surface, atmosphere, and clouds absorb a portion of incoming solar radiation, thereby increasing temperatures. Energy as longwave radiation (heat) is re-emitted to the atmosphere, clouds, or space, thereby reducing temperatures at the source. If the absorbed solar radiation and emitted heat are in balance, the Earth's temperature remains constant.



The Earth's radiation balance is the main driver of our climate. Image courtesy of National Aeronautics and Space Administration (NASA undated).

Natural factors contributing to past climate change are well documented and include changes in atmospheric chemistry, ocean circulation patterns, solar radiation intensity, snow and ice cover, Earth's orbital cycle around the sun, continental position, and volcanic eruptions. While these natural factors are linked to past climate change, they are also incorporated in the analysis of current climate change.

Since the Industrial Revolution, global climate has changed faster than at any other time in Earth's history (Mann et al. 1999). This rapid rate of change—often referred to as human-caused climate change—has resulted from changes in atmospheric chemistry, specifically increases in greenhouse gases due to increased combustion of fossil fuels, land-use change (e.g., deforestation), and fertilizer production (Figure 2-1) (Forster et al. 2007). The primary greenhouse gases in the Earth's atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), and ozone (O_3).

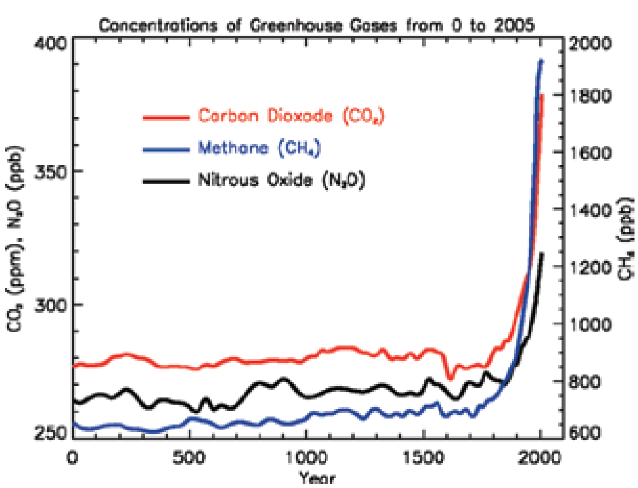


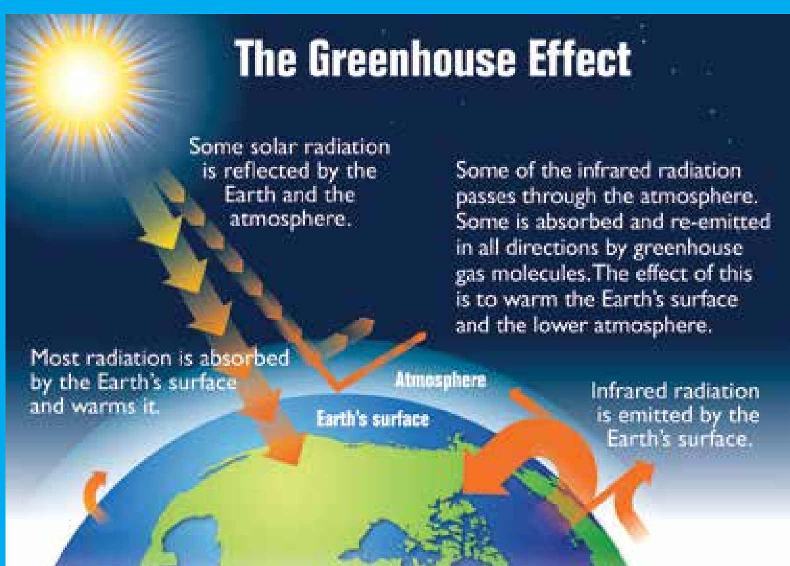
Figure 2-1. Changes in important global atmospheric greenhouse gas concentrations from year 0 to 2005 AD (ppm, ppb = parts per million and parts per billion, respectively) (Forster et al. 2007).

Incoming solar radiation is either absorbed, reflected, or re-radiated from the Earth's surface. Since greenhouse gas concentrations are greatest near the surface, a large fraction of this reflected and re-radiated energy is absorbed in the lower portions of the atmosphere (hence the increase in surface temperatures and the term "greenhouse effect"—see sidebar). For the total energy budget to balance, the energy (and temperature) at the top of the atmosphere must decrease to account for the increase of energy (and temperature) near the Earth's surface.

At natural levels, greenhouse gases are crucial for life on Earth; they help keep average global temperatures above freezing and at levels that sustain plant and animal life. However, at the increased levels seen since the Industrial Revolution (roughly 275 ppm then, 400 ppm now; Figure 2-1), greenhouse gases are contributing to the rapid rise of our global average temperatures by trapping more heat, often referred to as human-caused climate change. In the following chapters, we will refer to the impacts and effects of climate change as a result of both natural variability and human-caused climate change.

The Greenhouse Effect

The Earth's climate is driven by the sun. The high temperature of the sun results in the emission of high energy, shortwave radiation. About 31% of the shortwave radiation from the sun is reflected back to space by clouds, air molecules, dust, and lighter colored surfaces on the earth. Another 20% of the shortwave radiation is absorbed by ozone in the upper atmosphere and by clouds and water vapor in the lower atmosphere. The remaining 49% is transmitted through the atmosphere to the land surfaces and oceans and is absorbed. The Earth's surface re-emits about 79% of the absorbed energy as longwave radiation. Unlike shortwave radiation, the Earth's atmosphere absorbs approximately 90% of the longwave radiation emitted from objects on its surface. This results because of the presence of gases such as water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and various industrial products (e.g. chlorofluorocarbons; CFCs) that more effectively absorb longwave radiation. In turn, the energy absorbed by these gases is reradiated in all directions. The portion that is redirected back towards the surface contributes to warming and a phenomenon known as the greenhouse effect.



Climate change occurs when the Earth's energy budget is not in balance. Such change generally takes place over centuries and millennia. Human-caused climate change has been occurring over the last 200 yr, largely because of the combustion of fossil fuels and subsequent increase of atmospheric CO_2. Carbon dioxide, as well as CH_4 and other gases, absorb and re-emit longwave radiation back to the earth's surface that would otherwise radiate rapidly into outer space, thus warming the Earth. This increase in incoming longwave radiation is the greenhouse effect. Image courtesy the National Academies of Sciences (NAS undated).

CLIMATE CHANGE ASSESSMENTS

A growing awareness of our changing global climate since the 1950s has led to a substantial body of research. For example, the National Academy of Sciences (NAS 2011) report, *American's Climate Choices*, stated:

> *Climate change is occurring, is very likely caused primarily by human activities, and poses significant risks to humans and the environment. These risks indicate a pressing need for substantial action to limit the magnitude of climate change and to prepare for adapting to its impacts.*

In 1990, the United Nations tasked the Intergovernmental Panel on Climate Change (IPCC, see sidebar) with assessing existing research on climate change. Since then, five IPCC assessments have increased our scientific understanding of, and certainty about, global climate change. As described later in this chapter, the assessments have incorporated increasingly sophisticated models and analyses that consider both natural and human contributions to changes in our climate system.

In its most recent Fifth Assessment Report, the IPCC raised the likelihood of changes in several global climate events to "virtually certain" (i.e., 99-100% likelihood). Examples of these events include: more frequent hot days, less frequent cold days, reductions in permafrost, and sea-level rise (IPCC 2014).

What is the IPCC?

The Intergovernmental Panel on Climate Change is the leading international body for the assessment of climate change. It was established in 1988 by the United Nations Environment Programme and the World Meteorological Organization, and subsequently endorsed by the United Nations General Assembly. The goal of the IPCC is to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socioeconomic impacts.

IPCC
INTERGOVERNMENTAL PANEL ON climate change
WMO
UNEP

Recently, the third National Climate Assessment, produced in collaboration with the US Global Change Research Program, provided further insight into the anticipated climate changes for the conterminous US. The National Climate Assessment (NCA 2014) states:

> *Evidence for changes in Earth's climate can be found from the top of the atmosphere to the depths of the oceans. Researchers from around the world have compiled this evidence using satellites, weather balloons, thermometers at surface stations, and many other types of observing systems that monitor the Earth's weather and climate. The sum total of this evidence tells an unambiguous story: the planet is warming.*

MONTANA'S OBSERVED CLIMATE

To put future Montana climate change in perspective, we must first understand Montana's baseline (i.e., historical) conditions. In this section, we describe our state's unique geography and topography, as well as current climatology and the historical climate trends that have led us to the present day.

Geography and topography

Montana is the fourth largest state in the nation, with a land area that covers 147,164 mile^2 (381,153km^2). The state includes the beginnings of three major river basins. Two of these—the basins of the Columbia and the Missouri rivers—encompass almost 1/3 of the landmass of the conterminous United States (Figure 2-2). Consequently, Montana's climate influences the water supply for a large portion of the country, and its water supports tourism, agriculture, and ecosystems far beyond its borders. These attributes contribute to Montana's reputation as the premiere headwaters state and as "The Last Best Place."

Figure 2-2. Montana is the fourth largest state in the nation and provides the headwaters for three major river basins. Two of these, the Columbia and the Missouri, encompass almost 1/3 of the landmass of the conterminous US. The Continental Divide is the line running through the state, and forming the Montana/Idaho border until reaching Wyoming.

Montana's complex geography and topography contribute to a diverse climate. The state extends from below the 45th up to the 49th parallel. Given this (relatively) high latitude, Montana receives less energy from the sun and experiences cooler temperatures than many other areas of the US. Additionally, Montana's latitude and location within North America expose the state to a mix of diverse weather systems that commonly originate either from the Pacific Ocean or the Arctic, and sometimes from subtropical regions.

Topographically, the state's diverse mountain and prairie landscapes (approximately 40 and 60% of the area, respectively) include elevations that range from over 12,000 ft (3660 m) in southern Montana to 1800 ft (550 m) in eastern Montana. A number of island mountain ranges also occur in the plains east of the Continental Divide amid the vast prairie landscape.

The western portion of Montana contains approximately 100 named mountain ranges that form the Rocky Mountain Continental Divide. The Continental Divide (Figure 2-2) effectively splits the state into climatically distinct western and eastern regions. The Continental Divide squeezes out moisture from eastward flowing Pacific Maritime air, creating wet and dry halves to the state. The Continental Divide runs approximately north to south, from the Canadian border to the Idaho/ Wyoming border.

The mountainous area west of the Continental Divide has a climate similar to the maritime climates of the interior Pacific Northwest, with milder winters, cooler summers, and more year-round precipitation. Inversions, low clouds, and fog often form in valleys west of the Continental Divide. East of the Continental Divide, the prairie landscapes experience a semi-arid continental climate, with warmer summers, colder winters, and less precipitation.

Climate divisions

Montana's unique geography means climate varies across the state, as it does across the nation. Thus, throughout this Montana Climate Assessment, we aggregate past climate trends and future climate projections into seven Montana climate divisions, as shown in Figure 2-3. These seven climate divisions are a subset of the 344 divisions defined by the National Oceanic and Atmospheric Administration (NOAA) based on a combination of climatic, political, agricultural, and watershed boundaries (NOAAa undated). The history of the US Climate Divisions takes many twists and turns; it is well documented in Guttman and Quayle (1996).

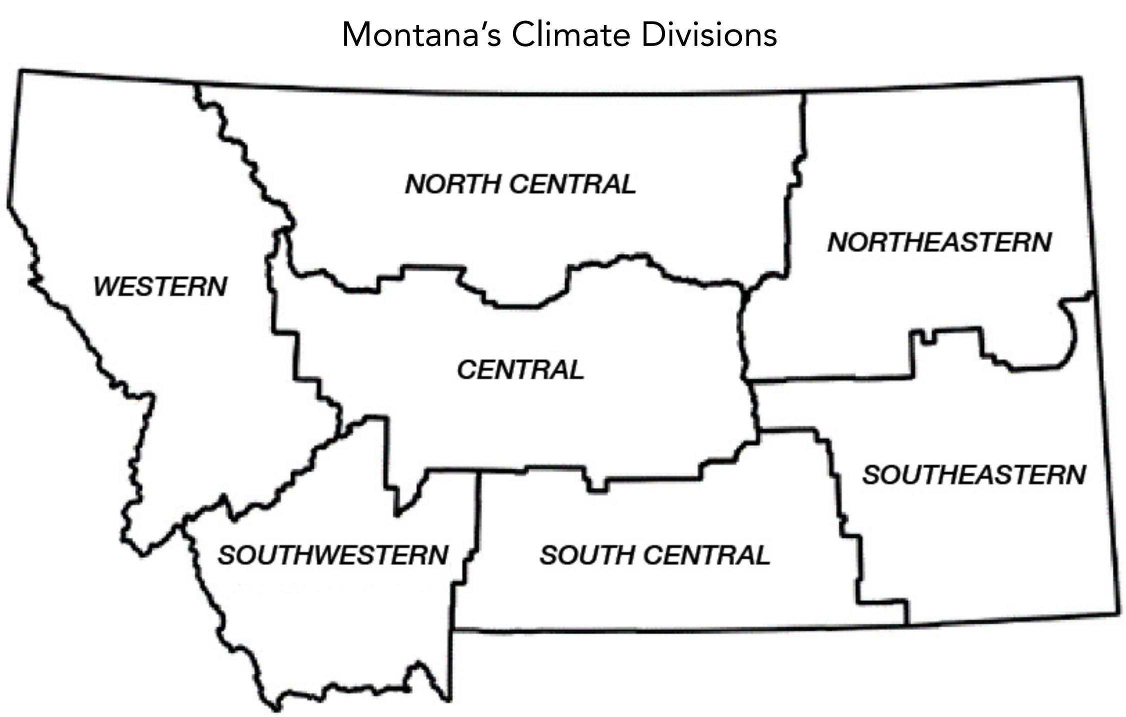


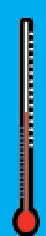
Figure 2-3. Montana's seven climate divisions.

Current climate conditions 1981-2010

To assess Montana's current climate, we analyzed climate variable data (see sidebar) provided as 3-decade averages by NOAA's National Centers for Environmental Information (NOAAb undated). In this section, we review average temperature and precipitation conditions from 1981-2010 as an indicator of current climate conditions.[5] In the next section on historical trends, we discuss changes in Montana's temperature, precipitation, and extreme events that have occurred over a longer time horizon.

Climate Variables

In analyses of climate, scientists employ a suite of 50 essential climate variables to unify discussions (Global Climate Observing System undated). For this assessment, we primarily focus on just two: how climate change will affect Montana's temperature and precipitation in the future.



Temperature is an objective measure of how hot or cold and object is with reference to some standard value. Temperature differences across the Earth result primarily from regional differences in absorbed solar radiation. Seasonal variations in temperature result from the tilt of the Earth's axis as it rotates around the sun.

Precipitation is the quantity of water (solid or liquid) falling to the Earth's surface at a specific place during a given period. Like temperature, precipitation varies seasonally and from place to place. Precipitation amounts can have a dramatic impact on local environmental conditions, such as abundance of wildlife or potential for crop production.

[5] The 3-decade averages are often termed *climate normal* periods and produced once every 10 yr. This assessment represents the first update for Montana's climate since the last climate normal period of 1970-2000. Analysis over the current climate normal period allows the best possible insight into the present state of Montana's climate, though it may not be what Montanan's, especially older Montanans, might consider normal. For more detail on our methods and results from this analysis, see Appendix 2-1 on the MCA website.

Temperature.—Table 2-1 shows the average seasonal temperature variation across Montana's seven climate divisions (Figure 2-3) from 1981-2010. Temperatures vary widely across Montana and are strongly dependent on local elevation and proximity to the Continental Divide. Western Montana's annual average temperatures are generally cooler (approximately 39°F [3.9°C]) relative to the eastern and central parts of the state (approximately 44°F [6.7°C]).

Table 2-1. Average temperatures (°F) for the seven Montana climate divisions from 1981-2010.[a,b]

Montana climate division	Annual	Winter (avg / avg minimum)	Spring	Summer (avg / avg maximum)	Fall
Northwestern	40.6	23.7 / 16.5	39.4	58.5 / 72.0	40.6
Southwestern	38.9	21.2 /12.4	37.3	57.5 / 71.5	39.4
North central	42.8	21.8 / 10.9	42.1	63.8 / 78.3	43.1
Central	43.3	24.8 / 14.6	41.8	62.7 / 77.1	43.5
South central	44.0	24.6 / 14.2	42.5	64.3 / 78.8	44.2
Northeastern	43.4	18.3 / 7.9	43.3	67.4 / 81.6	44.0
Southeastern	45.5	22.8 / 11.7	44.6	68.6 / 83.2	45.8

[a] For the purposes of this table, and indeed the entire MCA, we define the seasons as winter (December-February), spring (March-May), summer (June-August), and fall (September-November).

[b] To aid readability, we provide only °F. Temperature in Celsius can be calculated from: °C = (°F-32)/1.8

Winters in Montana are cold, with statewide average temperatures of 22°F (-5.6°C). Between cold waves there are often periods of mild, windy weather in central Montana created by persistent, moist Pacific air masses on the west side of the Continental Divide, and the drying and warming effects as air descends on the east side of the Rockies. These surface winds are locally known as *chinook winds* and can bring rapid temperature increases of 40-50°F (22-28°C) to areas east of the Rockies that can last for days.

Montana springs are highly variable and bring dramatic temperature changes. As a whole, Montana's average spring temperature is 42°F (5.5°C), although western Montana is cooler and warming comes later due to persistence of Pacific maritime air. In contrast, warmer continental air contributes to average temperatures up to 45°F (7.2°C) in spring across central and eastern Montana.

Elevation and proximity to the Continental Divide strongly influence local temperatures in summer. Valleys and the eastern plains are generally warmer than the higher elevations of the Continental Divide. While summer average temperature across Montana is 64°F (17.8°C), temperatures generally peak in July and August, with mean daily highs above 90°F (32°C) in the east, as well as in western valleys.

Fall temperatures in Montana are often highly variable, with an average temperature of 43°F (6.1°C). Days to weeks of warm temperatures are commonly followed by freezing temperatures that bring frosts and snow.

Precipitation.—In general, Montana is a water-limited, semi-arid landscape where precipitation is depended upon heavily by plants and animals alike. Table 2-2 shows the seasonal variation of precipitation across Montana's seven climate divisions (Figure 2-3) from 1981-2010. Precipitation amounts and form (rain versus snow) vary widely across the state and are strongly influenced by elevation and proximity to the Continental Divide. The average annual precipitation for Montana is 18.7 inches (0.47 m). Western Montana typically receives twice as much precipitation annually as eastern Montana (22-30 inches [0.56-0.76 m] versus 12-14 inches [0.30-0.36 m], respectively). The combination of moisture-rich maritime air from the Pacific in the winter, spring, and fall, and strong convective systems in the summer create a more evenly distributed year-round precipitation pattern in western Montana. In contrast, 65-75% of the annual precipitation occurs in the late spring and summer months for eastern and central Montana, coming from sources in the subtropical Pacific and Gulf of Mexico.

Table 2-2. Average precipitation in inches (cm) for the seven Montana climate divisions from 1981-2010.

Montana climate division	Annual	Winter	Spring	Summer	Fall
Northwestern	32.4 (82.2)	9.4 (23.9)	8.9 (22.6)	6.1 (15.5)	8.1 (20.6)
Southwestern	21.2 (53.8)	4.1 (10.4)	7.1 (18.0)	5.5 (14.0)	4.6 (11.7)
North central	15.1 (38.4)	1.9 (4.8)	4.6 (11.7)	5.5 (14.0)	3.1 (7.9)
Central	17.6 (44.7)	2.4 (6.1)	5.8 (14.7)	5.9 (15.0)	3.5 (8.9)
South central	18.4 (46.7)	2.7 (6.9)	6.4 (16.3)	5.2 (13.2)	4.2 (10.7)
Northeastern	12.8 (32.5)	1.0 (2.5)	3.7 (9.4)	5.7 (14.5)	2.4 (6.1)
Southeastern	13.8 (35.1)	1.2 (3.0)	4.6 (11.7)	5.1 (13.0)	2.9 (7.4)

The average statewide precipitation during winter is 3.3 inches (8.4 cm), though it varies considerably across the state. The majority of winter precipitation in Montana falls as snow, and the precipitation that accumulates as snowpack in the mountains is the most significant source of water to valley bottoms throughout the summer. Northwestern Montana receives an average of 9.4 inches (23.9 cm) of winter precipitation, but locally, and at higher elevations within the mountains, this value can increase to greater than 20 inches (50.8 cm). Eastern and central Montana typically receive 1.0-2.7 inches (2.5-6.9 cm) of winter precipitation.

Montana receives significant spring precipitation, with a statewide average of 5.8 inches (14.7 cm). Much of that precipitation contributes to the recharge of shallow soil moisture and groundwater supplies. This storage plays an important part in Montana's water cycle by releasing water slowly throughout the summer. Spring precipitation averages range from 7-9 inches (17.8-22.9 cm) in the west to 3-6 inches (7.6-15.2 cm) for prairie lands of central and eastern Montana.

The average summer precipitation for Montana, which is relatively consistent statewide, is 5.6 inches (14.2 cm). Convective thunderstorms are responsible for most of the summer precipitation across the state. These storms result from the uplift of warm, moisture-laden air masses originating from the subtropical Pacific and Atlantic. As the air rises, it cools and water vapor condenses, producing rainfall and, at times, large amounts of damaging hail.

The average fall precipitation for Montana is 4.1 inches (10.4 cm). Northwestern Montana experiences the largest average amount of precipitation (8.1 inches [20.6 cm]). Average fall precipitation declines as one moves to central and then eastern Montana (approximately 3.6 and 2.7 inches [9.1 and 6.9 cm], respectively).

Historical trends 1950 to present

We evaluated how temperature and precipitation have historically changed, dating back to mid-20th century. This review of historical trends helps us provide context for future climate change scenarios explored in later sections of this chapter. In addition, evaluating these trends can help us better understand a) how Montanans have previously experienced and responded to changing climate, b) if projections of future change reveal a different climate than we have previously experienced, and c) the potential impacts of that projected change.

We used standard statistical methods to analyze records of temperature and precipitation spanning two periods: 1950–2015 and 1900–2015.[6] The direction (increase or decrease) and significance of trends were generally similar for the two periods. As such, the presentation of trends that follows is confined to the period from 1950–2015. This is widely acknowledged as the benchmark period in climate analysis (Liebmann et al. 2010; IPCC 2013a), a period when our network of meteorological sensors becomes more accurate and sufficiently dense. It also coincides with an upward inflection of the annual average temperature trend for Montana, demarcating a time period with the highest rate of change and likely the strongest anthropogenic signal (NOAAc undated).

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[6] For more detail on our methods and results from this analysis, see Appendix 2-1 on the MCA website.

Our analysis uses observational data from the US Climate Divisional Database (NOAAc undated) to provide a more complete picture. The data were corrected to remove observational bias (e.g., station relocation, instrumentation changes, and observer practice changes) (Vose et al. 2014). Our approach included combining many stations to provide a more complete picture of historical changes for large regions. In our analyses, we determined if a detectable trend existed for temperature and/or precipitation across the seven climate divisions and/or the entire state. While not included in our analysis, other sources of historical climate data such as local observation are also extremely valuable to confirm measured trends and their impacts (see sidebar).

Crow Climate Observations

John Doyle and Margaret Eggers

As the Crow Environmental Health Steering Committee, a group of Crow Tribal stakeholders working on local water quality and health issues, we began discussing long-term changes in local climate and ecosystems we've observed in our lifetimes. This began a process of interviewing other Tribal members on this topic, and then comparing our community knowledge to climate and hydrological data available for the Crow Reservation and vicinity. We found that these two sources of data correspond and complement one another, with our observational data filling in gaps where no monitoring sites exist, and providing information on impacts to local foods, cultural traditions, and community health.

There is widespread agreement among Tribal Elders interviewed that winter snowfall is declining, winters are getting milder and summers are becoming hotter. The prairies used to be covered in deep snow from November to March, often making it difficult to feed livestock; the rivers would freeze up and as kids we could ice skate all winter long, including along the rivers. With winter, the wind would shift to come primarily from the north, instead of from the west—a sign to us that winter had come. Now the prairies are commonly barren of snow, rivers have thin ice if at all, and there are successive winter *days above freezing when the trees thaw out, only to be damaged when freezing conditions return. Sometimes a winter snowfall turns into rain, which never used to happen. It's hard to predict the winter weather anymore, as we once could in the old days. These changes also seem to affect community health: The long winter cold was associated with less illness; we associate the increasing incidence of colds and flu with milder winters.*

Around March, ice breakup on the river used to be a major event, scouring the riverbeds and leaving large chunks of ice to slowly melt on the riverbanks. This was accompanied by a traditional Crow ceremony. By April, the snow would be gone and brooks would be running everywhere. Now the thin ice simply melts away quietly, and the ephemeral brooks don't all flow. We would get storms when it would rain really hard for 10-15 minutes, now the spring storms come with severe winds and sleet or hail. However, spring flood events are more frequent now. Before the flood in the 1970s and the two severe floods in the past decade, the only one our parents remember was in 1921.

Summer heat lasts longer than it used to, and is more intense. We used to get summer rains that broke the heat, now that hardly happens anymore; when it stays hot for a long time, it seems to affect the vegetation. Plants are a good way of finding out the weather: when their leaves don't grow to their fullest, we know the weather, the climate, is changing. Boxelder trees and some of the berry shrubs along the river are slowly dying. Riparian berries, including plums, chokecherries, juneberries, and buffalo berries, have been gathered for generations as staple foods. Sometimes they now bloom earlier in the spring; cold snaps freeze the blossoms and the berry crops are lost. Sundances—a traditional outdoor ceremony in which both men and women dance, pray and fast without either food or water for 3 to 4 days—have always been held in the same locations in May and June. People who have sundanced over many years say it is becoming more difficult, as these months are increasingly hotter and drier. One Elder remarked that there were never any bad forest fires when he was a boy; those fires didn't start until the 1950s.

The disappearance of some insect species, the flocking of birds, animals growing thicker coats, and snow on the mountains were always signs of winter—it is now mid-November, still T-shirt weather with no snow on the mountains, and the grasshoppers and most summer birds are still around. We used to gather buffalo berries in the fall after the first frost sweetened the berries; now the first frost doesn't come before the berries dry up, so they aren't worth harvesting.

There are a lot of species which are no longer here or are rarely seen—perhaps due to climate changes, perhaps population. Barn owls, burrowing owls, snipes, certain hawks, prairie chickens, and blue grouse are gone. Kangaroo mice and another mouse that was always nesting used to be common. Frogs used to croak all night long in the summers, now you don't hear them anymore. Small turtles, freshwater mussels, and a riverbank lizard species have disappeared. In addition to the declining availability of berries, other food plants such as wild turnip and wild carrot, which used to be all over, have become scarce.

We all see these changes, but there seems to be a reluctance to talk about what's happening, to name it. As one Elder, G. Bulltail, concluded,

> *The rivers are powerful, they have energy and they make things grow. We used to go to the river to communicate with this energy, now we just go there to fish and to swim. Nature used to provide for us, and we put back what we got, but we don't do that anymore. Everything is getting polluted—the air isn't clean anymore. The Earth is trying to tell us that we have to go back to a time when we saw the energy in Earth, when we were compatible with Nature.*

CROW Environmental Health Steering Commitee

Image of Little Bighorn River courtesy John Doyle. John Doyle is a Crow Tribal Elder and Water Quality Project Director at Little Big Horn College. Mari Eggers is a Research Scientist at Montana State University Bozeman. The authors would like to acknowledge and thank Urban Bear Don't Walk, Grant Bulltail, Larry Kindness, MA LaForge, Bill Lincoln, Larson Medicine Horse, K. Red Star, David Small, Sara Young, and David Yarlott Jr for contributions to this article. Insignia provided by John Doyle and Mari Eggers with permission.

Temperature.—Table 2-3 shows the decadal rate of change from 1950-2015 for average annual temperatures across Montana. We provide that rate of change both annually and by season for the seven Montana climate divisions depicted in Figure 2-3. We also present the average annual and average seasonal changes statewide and for the US as a whole. To account partially for autocorrelation we considered trends as significant with a conservative p value at $p<0.05$. Generally, Montana has warmed at a rate faster than the annual national average, as well as within individual seasons.

Table 2-3. Decadal rate of change for annual average temperatures in °F (°C) for the seven Montana climate divisions (Figure 2-3), statewide, and US from 1950-2015. A value of 0 indicates no statistically significant change between decadal averages.

Montana climate division	Annual	Winter	Spring	Summer	Fall
Northwestern	+0.39 (+0.22)	+0.38 (+0.21)	+0.49 (+0.27)	+0.38 (+0.21)	+0.29 (+0.16)
Southwestern	+0.35 (+0.19)	0 (0)	+0.58 (+0.32)	+0.30 (+0.17)	+0.23 (+0.13)
North central	+0.51 (+0.28)	+0.85 (+0.47)	+0.62 (+0.34)	+0.30 (+0.17)	0 (0)
Central	+0.43 (+0.24)	+0.59 (+0.33)	+0.59 (+0.33)	+0.29 (+0.16)	0 (0)
South central	+0.44 (+0.24)	+0.49 (+0.27)	+0.61 (+0.34)	+0.36 (+0.20)	+0.30 (+0.17)
Northeastern	+0.48 (+0.27)	+0.78 (+0.43)	+0.65 (+0.36)	+0.26 (+0.14)	0 (0)
Southeastern	+0.40 (+0.22)	+0.59 (+0.33)	+0.56 (+0.31)	0 (0)	0 (0)
Statewide	+0.42 (+0.23)	+0.56 (+0.31)	+0.40 (+0.22)	+0.30 (+0.17)	+0.25 (+0.14)
US	+0.26 (+0.14)	+0.30 (+0.17)	+0.40 (+0.22)	+0.18 (+0.10)	+0.18 (+0.10)

Average annual temperatures increased for the entire state and within all climate divisions (see Figure 2-3). The rate of temperature increase was 0.4°F/decade (0.2°C/decade) across the state, and this rate was relatively constant across all climate divisions (Table 2-3). Similarly, average annual maximum and minimum temperatures increased statewide, and for all seven climate divisions, by 0.3-0.6°F/decade (0.2-0.3°C/decade). Between 1950 and 2015, Montana's average annual temperature has increased by 2.7°F (1.5°C); annual maximum and minimum temperatures have increased approximately 3.3°F (1.8°C).

Between 1950 and 2015, average annual temperature increased for the entire state of Montana and within all climate divisions. The state average annual temperature increased 2.7°F (1.5°C); annual maximum and minimum temperatures increased approximately 3.3°F (1.8°C).

MT Climate Division Temperature Trends from 1950–2015

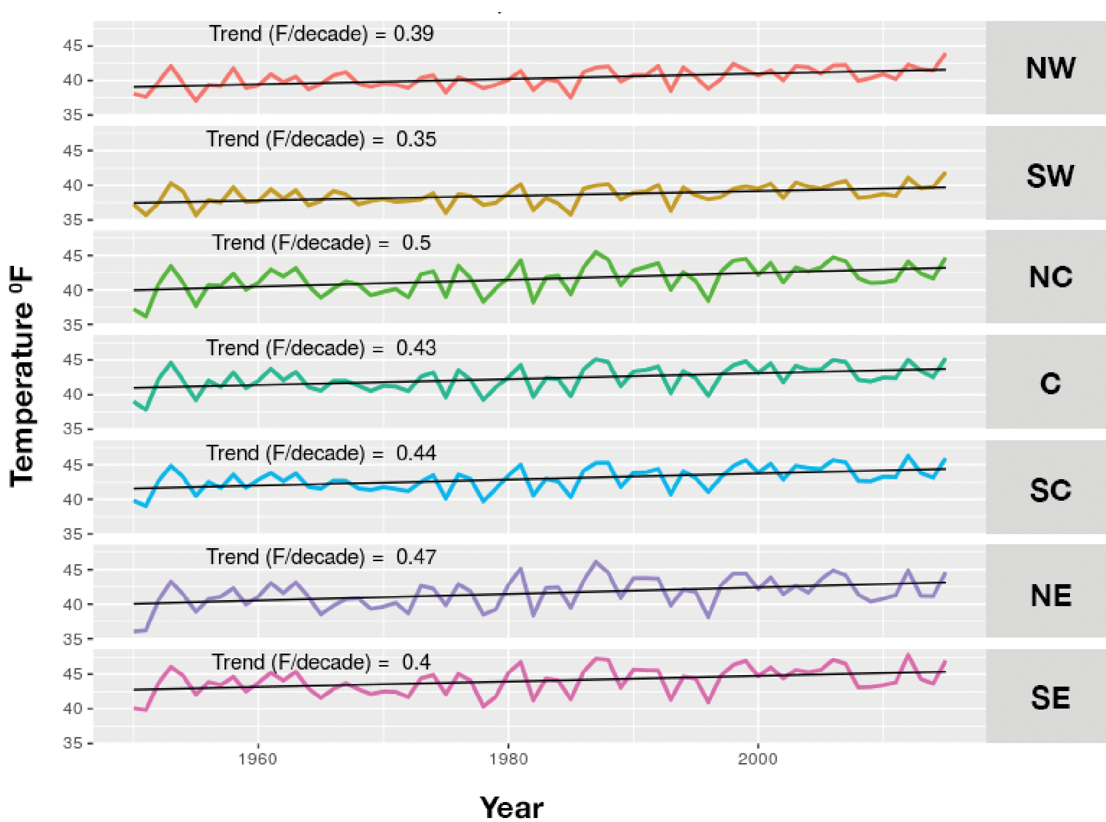

Figure 2-4. Trends in annual average temperature across each climate division (Figure I) in Montana. The divisions are northwestern (NW), southwestern (SW), north central (NC), central (C), south central (SC), northeastern (NE), and southeastern (SE).

Precipitation.—Annual precipitation averaged across the state has not changed significantly since 1950. Some change, however, has occurred within different climate divisions and for different seasons as shown in Table 2-4. We found no significant changes in summer and fall precipitation between 1950-2015 for any climate division. Seasonally, the largest changes—declines—in precipitation (rain and snow combined) have occurred during winter months (Table 2-4). We used a smaller p value (<0.05) to determine statistical significance of trends and to account for potential autocorrelation of time series data. Our analysis suggests that an increase in the number of El Niño events since 1950 has contributed to drier winters and decreased precipitation for Montana's northwestern, north central, and central climate divisions (see Teleconnections section for more on the El Niño Southern Oscillation). In the eastern portions of the state significant increases in precipitation have occurred during the spring months (Table 2-4).

Table 2-4. Decadal rate of change in average precipitation in inches/decade (cm/decade) for the seven Montana climate divisions (Figure 2-3), statewide, and US from 1950-2015. A value of 0 indicates no significant change.

Montana climate division	Annual	Winter	Spring	Summer	Fall
Northwestern	-0.58 (-1.5)	-0.57 (-1.4)	0	0	0
Southwestern	0	0	0	0	0
North central	0	-0.09 (-0.23)	0	0	0
Central	0	-0.11 (-0.28)	0	0	0
South central	0	0	0	0	0
Northeastern	0	0	+0.21 (+0.53)	0	0
Southeastern	+0.35 (+0.89)	0	+0.30 (+0.76)	0	0
Statewide	0	-0.14 (-0.36)	0	0	0
US	+0.33 (+0.84)	0	+0.08 (+0.20)	+0.08 (+0.20)	+0.16 (+0.41)

Extreme aspects of Montana's climate.—Along with analyzing historical trends in temperature and precipitation, we performed an analysis of changes in extreme climate events since the middle of last century. Two examples of climate extremes include periods of intense warm or cool temperatures and significant wet or dry spells across seasons. Because these events affect every aspect of our society, decision makers and stakeholders are increasingly in need of historical evaluations of extreme events and how they are changing from seasons to centuries. The coldest temperature ever observed in the conterminous US was -70°F (-57°C) at Rogers Pass outside of Helena on January 20, 1954 (see sidebar). Since 1950, however, our analysis shows the average winter temperature has increased by 0.4°F/decade (0.2°C/decade) across the state, with an overall average winter temperature increase of 3.6°F (2.0°C). Average spring temperatures have increased by 2.6°F (1.4°C) during the same period, and average summer temperatures have risen by 2.0°F (1.1°C). Montana's fall average temperatures have increased by 1.6°F (0.9°C) since 1950.

Rogers Pass,Montana

C. Corby Dickerson IV

One-half mile west of Rogers Pass and just south of the Continental Divide, a humble cabin was nestled next to a fledgling gold mine. The cabin sat within a small, "saucer-shaped depression" in the hills. It was 1954. The weather had been unrelenting: heavy, intense snow had fallen near continuously for 7 days, totaling over 5 ft (1.5 m) deep by 5 PM on the 19th of January. The temperature that morning had been a frigid -37°F (-38°C). But, unbelievably, these measurements themselves would ultimately pale in comparison to what would occur later that night.

Meteorologically, conditions had been ideal for a prolonged, heavy snow event. A steady feed of relatively warm and very moist Pacific air had, for several days, rested over a comparatively dry and persistent Arctic air mass from Canada. As the sun set on the horizon, the snow ceased and the wind, which had been biting from the northeast for days, was notably weaker. After settling in for another night of trying to stay warm in his family's primitive surroundings, official US Weather Bureau observer

H.M. Kleinschmidt resolved to stay awake much of the night due to, as described by Dightman (1963),

> *… loud and frequent "popping" noises in the cabin, and that about 2 AM on the 20th he had observed his [unofficial] thermometer (exposed outside an insulated window several inches from the building) to show about -68°F.*

Mr. Kleinschmidt, despite the extreme and dangerous cold, ventured outside to check the official instrument shelter where he found the minimum thermometer to read colder than -65°F (-54°C), which was as far down the scale as the government-issued thermometer could read. Later that day at observation time, he recorded the minimum temperature as -68°F (-56°C), completely unaware that this would come to set a record for the coldest reading ever taken in the United States! Thereafter, the Kleinschmidts went about their business as rugged Montana miners, while the weather gradually returned to more normal January conditions.

Although this record temperature occurred on January 20th, the Weather Bureau remained unaware of it until the observation form arrived at its Helena office on February 3rd. In reviewing this data, program manager and State Climatologist R. A. Dightman immediately noted the remarkable reading. Believing it to be a potential record, Dightman contacted the observer, requesting he send in the minimum thermometer for evaluation. The Kleinschmidts had been noted as doing "very well and keep[ing] a good record"as observers (Dightman 1963). (It is standard practice to send instrumentation to the US Weather Bureau lab in

Washington, DC for calibration and verification when such extreme records are possible.) Yet Kleinschmidt, the good observer he was, actually did one better and sent in both the official minimum thermometer and his personal minimum thermometer for evaluation.

While in the lab, scientists recreated the extreme conditions and observed the official and unofficial thermometers just as Kleinschmidt had described: the marker floating in the official liquid thermometer retreated back into its bulb and remained stuck there, pinned at an angle against the glass. This made it impossible for an actual reading much below the scale of this thermometer. But through additional laboratory analysis, along with the verified reading on the unofficial minimum thermometer, the US Weather Bureau was able to declare the coldest temperature observed that morning as -69.7°F (-57°C). Now confirmed as a valid observation, this reading was cross-checked against additional nearby stations (which had recorded -57°F [-49°C] and -59°F [-51°C] that same day) for reasonable consistency. After passing this final test and by knowing that they were good observers who were unaware of the potentially record-breaking nature of this observation, the US Weather Bureau on March 16, 1954 accepted the -70°F (-57°C) reading as the official all-time record low for the US. Seventeen years later a reading of -79.8°F (-62°C) was observed at Prospect Creek Camp in Alaska, establishing a new record for the country. However, to this day the reading at Rogers Pass, Montana is still the coldest ever observed throughout the conterminous US—a reading that astounds as much as it reveals about the limitlessness of nature.

This highway marker near Rogers Pass commemorates the record cold of 1954. C. Corby Dickerson IV is a General Forecaster with the National Weather Service in Missoula, MT who also leads various graphical and social media programs. The author acknowledges a) Chris Gibson and Paul Fuhr for their editing assistance; and b) Matt Moorman, Michael Zenner, Dave Bernhardt, Gina Loss, and the staff at the National Centers for Environmental Information for their valuable assistance in helping track down the story behind this historic observation.

We performed our analysis of climate extremes using the CLIMDEX project (CLIMDEX undated), which provides a collection of global and regional climate data from multiple sources. CLIMDEX is developed and maintained by researchers at the Climate Change Research Centre and the University of New South Wales, in collaboration with the University of Melbourne, Climate Research Division of Environment Canada, and NOAA's National Centers for Environmental Information. The CLIMDEX project aims to produce a global dataset of standardized indices representing the extreme aspects of climate. Particular attention was placed on the changes in variables such as consecutive dry days, days of heavy precipitation, growing season length, frost days, number of cool days and nights, and the number of warm days and nights. Extreme precipitation events across the United States have increased in both intensity and frequency since 1901 (NCA 2014), including across both the High Plains and the northwestern US (many states combined), where studies have shown an increase in the number of days with extreme precipitation (NCA 2014). However, for our analysis at the state level we found no evidence of changes in extreme precipitation so it is not a variable of focus. Here, we report those variables that did change significantly ($p<0.05$) for Montana and, for perspective, the climate normals for these extremes for the periods 1951–1980 and from 1981-2010 (Table 2-5).[7]

Table 2-5. Changes in Montana's climate extremes. Here, we report those variables that changed significantly for Montana. For historical perspective, we also report the climate normal for these extremes from the periods 1951-1980 and from 1981-2010.

Variable	Change (1951-2010)	1951–1980	1981–2010
Warm days	11 days	30 days	41 days
Cool days	-13 days	43 days	30 days
Frost days	-12 days	171 days	159 days
Growing season	12 days	194 days	206 days
Warm nights	14 nights	30 nights	44 nights
Cool nights	-12 nights	43 nights	31 nights
Monthly minimum temperature	5°F (2.8°C)	-25°F (-32°C)	-20°F (-29°C)
Monthly maximum temperature	1.1°F (0.6°C)	97.5°F (36°C)	98.6°F (37°C)

[7] For more detail on our methods, data, and results from this analysis, see Appendix 2-1 on the MCA website.

The annual number of cool days and the number of days with frost are decreasing across Montana. We use the CLIMDEX definition of *cool days* as the percentage of days when maximum temperature is lower than 10% of the historical observations. Coincident with warming temperatures, the number of cool days each year during the period from 1951–2010 has decreased by 13.3 days. Along with this trend, the number of days in which the minimum temperatures are below 32°F (0°C; i.e. *frost days*) has decreased by 12 days during this time period. These trends have contributed to an overall increase in the *growing season length* of 12 days between 1951 and 2010. In addition, the number of *warm days*, where maximum temperature exceeds 90°F (32°C) based on historical conditions, has increased by 11 days over this period. At a sub-annual level, monthly maximum and minimum temperatures have also changed. These are defined as the monthly maximum (minimum) value of daily maximum (minimum) temperatures. Monthly minimum values of daily minimum temperatures have increased by 5°F (2.8°C) from the period 1951–2010. Over the same time period, monthly minimum values of daily maximum temperatures have increased by 1.1°F (0.6°C).

There has been an increase in the number of warm nights and a related decrease in the number of cool nights across Montana. We use the CLIMDEX definition of *warm nights* (and *cool nights*) as the number of days when minimum temperature is higher (lower) than a specified maximum (minimum) threshold defined by historical conditions. The number of warm nights has increased by 11 days from 1951 to 2010. The number of cool nights has decreased by 12 days over this same period. These trends are in agreement with observations across many portions of the continental US (Davy and Esau 2016).

Between 1951 and 2010, the growing season in Montana increased 12 days.

Drought

Drought is a recurrent climate event that may vary in intensity and persistence by region. Drought can have broad and potentially devastating environmental and economic impacts (Wilhite 2000); thus, it is a topic of ongoing, statewide concern.

Through time, Montana's people, agriculture, and industry, like its ecosystems, have evolved with drought. Today, many entities across the state address drought, including private and non-profit organizations, state and federal agencies, and landowners, as well as unique watershed partnerships.

Drought is a complex phenomenon driven by both climate, but also affected by human-related factors (e.g., land use, water use). Although the definition of drought varies in different operational contexts, most definitions include several interrelated components, including:

- meteorological drought, *defined as a deficit in precipitation and above average evapotranspiration that lead to increased aridity;*
- hydrological drought, *characterized by reduced water levels in streams, lakes, and aquifers following prolonged periods of meteorological drought;*
- ecological drought, *defined as a prolonged period over which an ecosystem's demand for water exceeds the supply (the resulting water deficit, or shortage, creates multiple stresses within and across ecosystems); and*
- agricultural drought, *commonly understood as a deficit in soil moisture and water supply that lead to decreased productivity (in this assessment, we will treat this form of drought as an important component of ecological drought).*

While the subsequent chapters dealing with water, agriculture, and forests treat the subject of drought differently, each describes drought within the context of one or more of the four definitions described above.

Teleconnections

When we think of weather, we generally think about what is happening around us at that moment. However, the Earth's atmosphere, oceans, and landmasses make up a continuous system, and what we experience as weather—and also in expanded time frames as climate—is actually a small part of much larger patterns of atmospheric circulation that determine movements of air, moisture, and energy across the planet. Atmospheric circulation takes on recurring patterns that link the weather and climate across distant parts of the globe. Scientists call these recurring or persistent patterns, teleconnections. Teleconnections thus are climate oscillations that link across vast geographical areas and can last for weeks to decades.

In the past, scientists identified teleconnections by observing patterns in historical climate and weather data, and then investigating the underlying processes driving those patterns. As global climate changes, the nature of these connections is changing, as well. We can no longer rely only on historical observations to understand future teleconnections. Thus, predicting climate-related changes in teleconnections and the impact of those changes on local weather and climate are important areas of ongoing research.

Scientists recognize many teleconnections. We describe two of the most important teleconnections for Montana below, the El Niño-Southern Oscillation and the Pacific Decadal Oscillation.[8] It is important to bear in mind that teleconnections are happening continually, and superimposed on each other as well as upon other long-term climate patterns. As such, teleconnections may mask the trend of a longer-term climate signal or enhance the signal making it appear stronger than it is. Additionally, teleconnections can be helpful in identifying likely seasonal and annual weather patterns and, in some cases, longer-term climate trends.

El Niño-Southern Oscillation.—

The El Niño-Southern Oscillation cycle refers to a fluctuation between unusually warm (El Niño) and cold (La Niña) waters in the tropical Pacific, with associated changes in atmospheric circulation (the Southern Oscillation) (Figure 2-5). El Niño and La Niña events typically develop over 2-7 yr. During El Niño events, western North America experiences greater flows of maritime air and reduced flows of cold polar air from Canada. Generally drier and warmer conditions result in the northwestern US (NWSa undated). In Montana, El Niño winters receive roughly 70-90% of normal precipitation, and both winter and summer are warmer than average (Figures 2-5 and 2-6) (NWSb undated; Higgins et al. 2007). The effects of La Niña events are generally opposite those of El Niño. The northwestern US, including Montana, experiences increased precipitation and cooler temperatures, while the southern states are drier and warmer during La Niña events.

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[8] Information on three other teleconnections that impact Montana's climate and weather can be found in Appendix 2-2 on the MCA website.

Typical January–March Weather Anomalies and Atmospheric Circulation During Moderate to Strong El Niño and La Niña

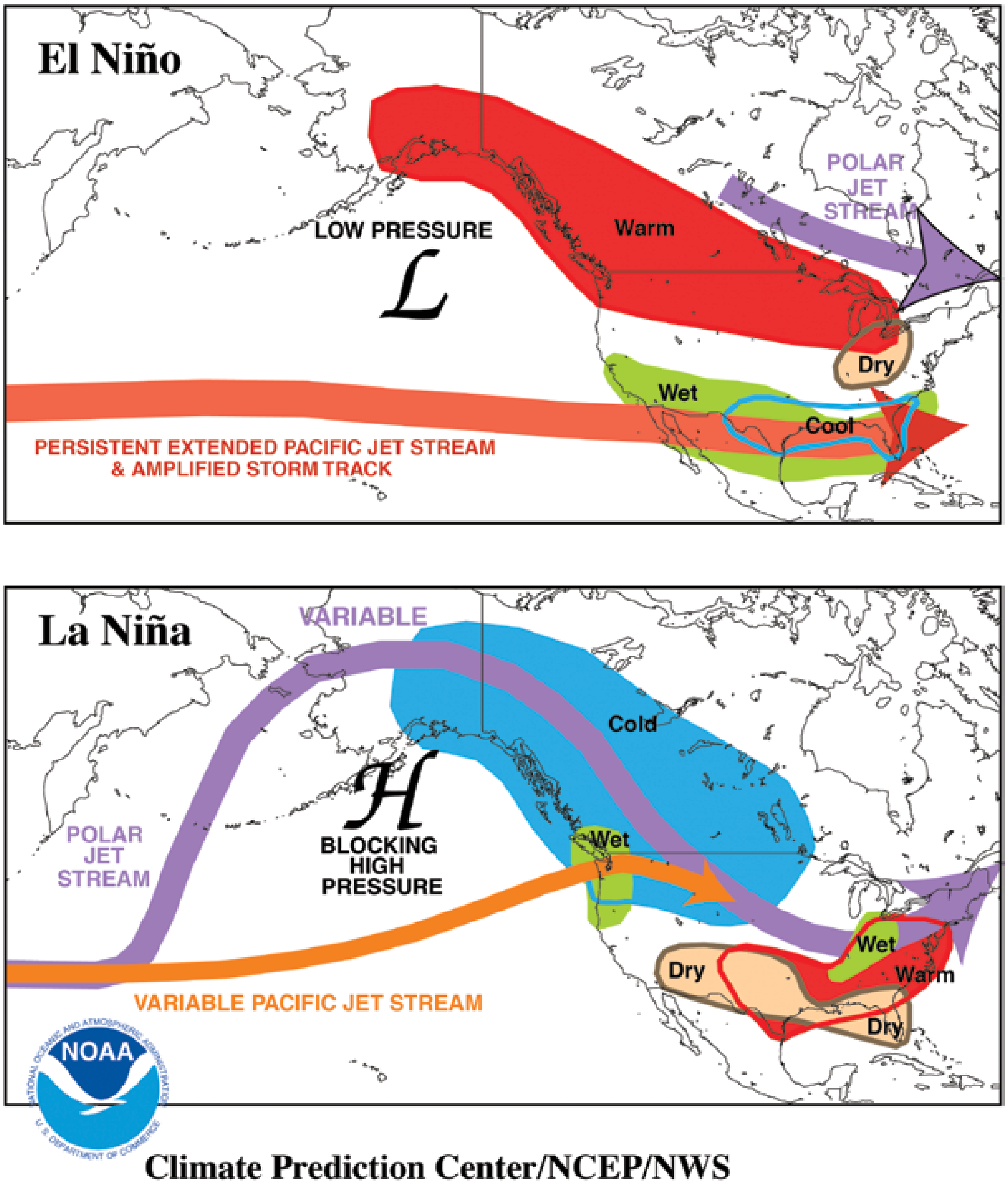


Figure 2-5. Typical January-March weather anomalies and atmospheric circulation during El Niño (top) and La Niña (bottom) events. Image courtesy National Weather Service (NWSa undated).

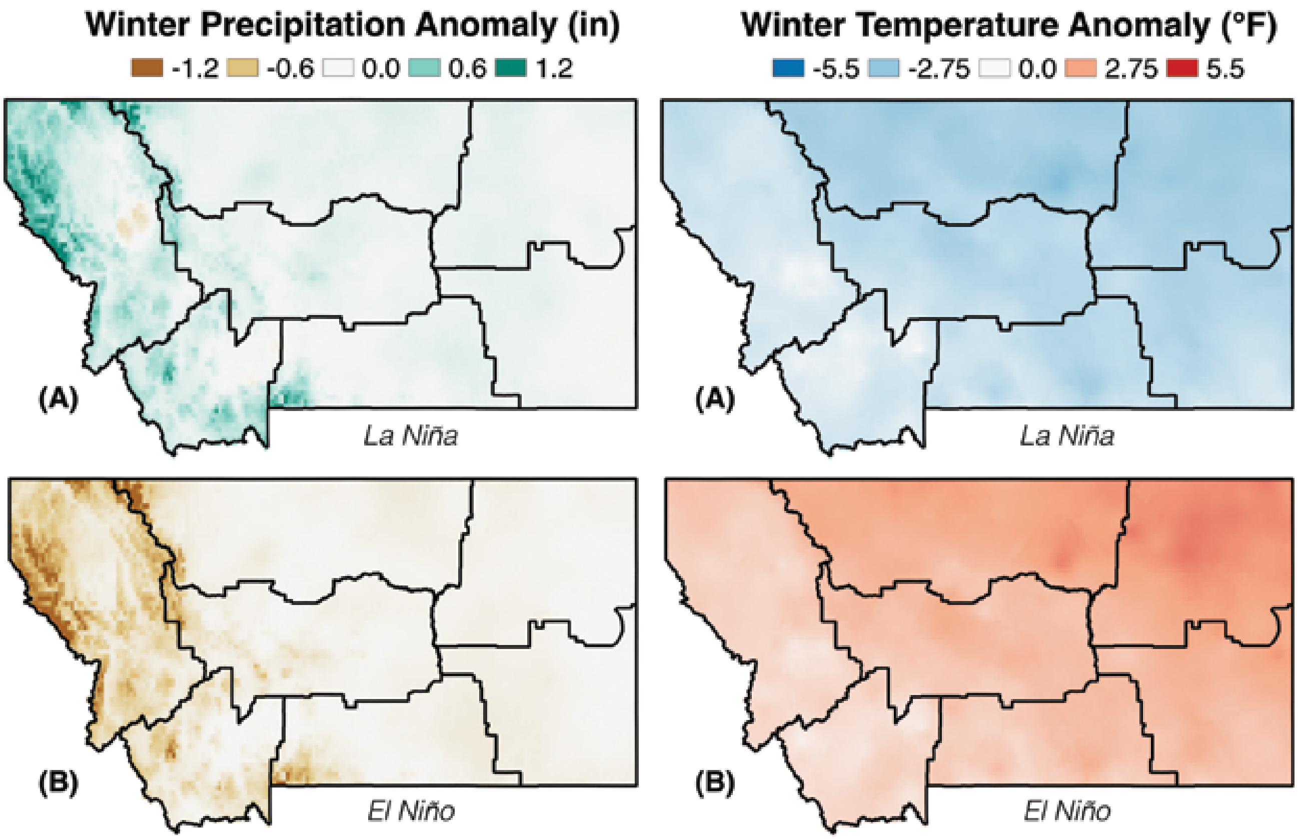


Figure 2-6. (A) Top two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during La Niña events. (B) Bottom two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during El Niño events. For Montana, El Niño winters are generally drier and warmer; La Niña winters are generally wetter and colder. This analysis was done using data from Livneh et al. (2013) and is based on the study period of 1915-2013.

Pacific Decadal Oscillation.—The Pacific Decadal Oscillation is a pattern of ocean-atmospheric climate variability across the mid-latitude Pacific Ocean. The oscillation varies in time from interannual to inter-decadal, with the strongest cycle typically occurring about every 30 yr. Effects of the Pacific Decadal Oscillation are not as intense as the El Niño-Southern Oscillation cycle (Mantua and Hare 2002). During its warm phase, winter temperatures are warmer throughout Alaska, western Canada, and the western US (by an average of 2°F [1.1°C]), and precipitation is decreased (Figure 2-7). Effects during the cool phase reverse, with cooler winter temperatures and increased precipitation experienced over western North America.

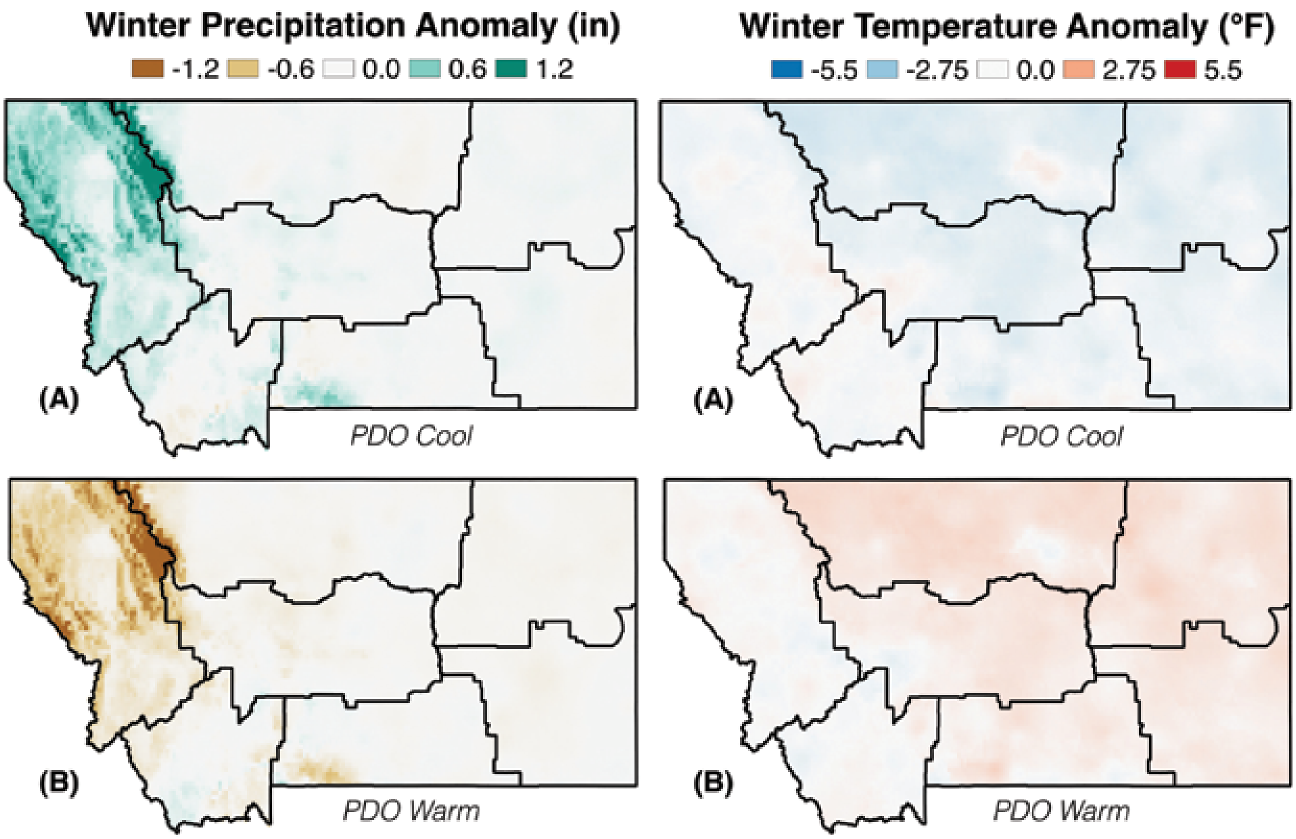


Figure 2-7. (A) Top two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during the cool phase of the Pacific Decadal Oscillation. (B) Bottom two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during the warm phase of the Pacific Decadal Oscillation. For Montana, the warm phase of the Pacific Decadal Oscillation is generally associated with warmer and drier winters. Cool phase Pacific Decadal Oscillation winters are generally wetter and colder. This analysis was done using data from Livneh et al. (2013) and is based on the study period of 1915-2013.

The Pacific Decadal Oscillation and El Niño-Southern Oscillation teleconnections may reinforce or moderate each other, depending on if their phases are in alignment or opposition.

FUTURE PROJECTIONS

Global Climate Modeling

Projecting future climate on a global scale requires modeling many intricate relationships between the land, ocean, and atmosphere. Many global climate and Earth system models exist, each varying in complexity, capabilities, and limitations.

Consider one of the simplest forms of a model used for future projections, a linear regression model (Figure 2-8). With this model, researchers would plot a climate variable (e.g., temperature) over time, draw a best-fit, straight line through the data, and then extend the line into the future. That line, then, provides a means of projecting future conditions. Whether or not those projections are valid is a separate question. For example, the model may be based on false assumptions: the relationship may a) not be constant through time, b) not include outside influences such as human interventions (e.g., policy regulations), and c) not consider system feedbacks that might enhance or dampen the relationship being modeled.

Example of Linear Regression Mode

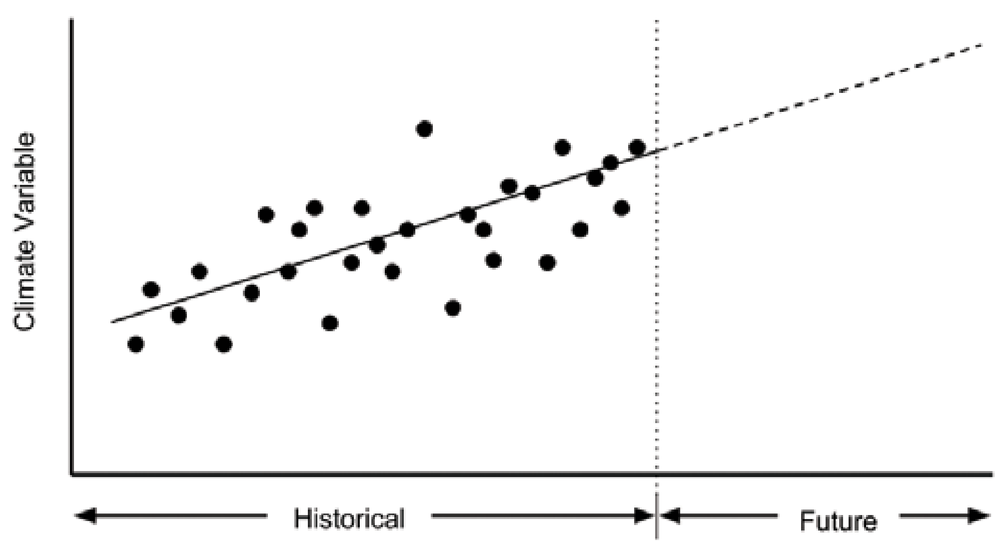


Figure 2-8. Example of a simple linear regression model of climate change. This model looks at the historical data of a climate variable (e.g., temperature) and has a best-fit line running through these data. This best-fit line follows the same trend into the future and can be used to project the change of the climate variable in the coming years. Such a model is useful to illustrate modeling principles, but it is too simple to accurately forecast future climate trends.

While the linear regression model provides an instructive visual aid for considering modeling, it is too simple for looking at climate changes, in which the interactions are complex and often nonlinear. For example, if temperatures rises, evaporation is expected to increase. At the same time, increasing temperatures increase the atmosphere's capacity to hold water. Water is a greenhouse gas so more water in the atmosphere means the atmosphere can absorb more heat…thus driving more evaporation. What seemed a simple relationship has changed (possibly dramatically) because of this feedback between temperature, evaporation, and the water-holding capacity of the atmosphere.

Linear models do not account for such nonlinear relationships. Instead, climate scientists account for nonlinearity through computer simulations that describe the physical and chemical interactions between the land, oceans, and atmosphere. These simulations, which project climate change into the future, are called general circulation models (GCMs; see sidebar).

General Circulation Models

General circulation models (GCMs) help us project future climate conditions. They are the most advanced tools currently available for simulating the response of the global climate system—including processes in the atmosphere, ocean, cryosphere, and land surface—to increasing greenhouse gas concentrations.

GCMs depict the climate using a 3-D grid over the globe, typically having a horizontal resolution of between 250 and 600 km (160 and 370 miles), 10-20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. Their resolution is quite coarse. Thus, impacts at the scale of a region, for example for Montana, require downscaling the results from the global model to a finer spatial grid (discussed later) (text adapted from IPCC 2013b).

Because of the complexities involved, climate scientists rarely rely on a single model, but instead use an ensemble (or suite) of models. Each model in an ensemble represents a single description of future climate based on specific initial conditions and assumptions. The use of multiple models helps scientists explore the variability of future projections (i.e., how certain are we about the projection) and incorporate the strengths, as well as uncertainties, of multiple approaches.

For the work of the Montana Climate Assessment, we employed an ensemble from the fifth iteration of the Coupled Model Intercomparison Project (CMIP5), which includes up to 42 GCMs depending on the experiment conducted (CMIP5 undated). The World Climate Research Program describes CMIP as "a standard experimental protocol for studying the output" of GCMs (CMIP undated). It provides a means of validating, comparing, documenting, and accessing diverse climate model results. The CMIP project dates back to 1995, with the fifth iteration (CMIP5) starting in 2008 and providing climate data for the latest IPCC Fifth Assessment Report (Stocker et al. 2013).

We employed 20 individual GCMs from the CMIP5 project for the Montana Climate Assessment ensemble, chosen because they provide daily outputs and a range of important climate variables.[9] For this first Montana Climate Assessment, we are only using climate variables of temperature and precipitation (later assessment may evaluate other important variables such as wind and relative humidity).

The benefits of using CMIP5 data are that each model in the ensemble a) has been rigorously evaluated, and b) uses the same standard socioeconomic trajectories—known as Representative Concentration Pathways (RCPs)—to describe future greenhouse gas emissions. RCPs are future greenhouse gas concentration scenarios.

Four RCP scenarios are available in CMIP5: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The number after RCP represents the increase in radiative forcing in watts/m^2 by the year 2100. Higher radiative forcing values are associated with larger amounts of trapped heat in the atmosphere due to increased greenhouse gas emissions (see sidebar). Simply stated, higher RCP values are typically associated with greater greenhouse gas emissions and therefore greater potential for climate change. Each RCP scenario makes different assumptions about future energy sources, population growth, economic activities, and technological advancements, as follows:

- RCP2.6.—The peak-and-decline scenario assumes greenhouse gas emissions peak between 2010-2020 and then decline by the end-of-century, leading to a radiative forcing of 2.6 watts/m^2. It assumes greenhouse gas emissions are substantially reduced over time (Van Vuuren et al. 2011).
- RCP4.5.—The stabilization scenario where technological advancements and strategies lead to a peak in greenhouse gas emissions at about 2040 followed by a decline (Clarke et al. 2007). We

9 Further detail on the 20 models employed in our ensemble, as well as our modeling process, see Appendix 2-1 on the MCA website.

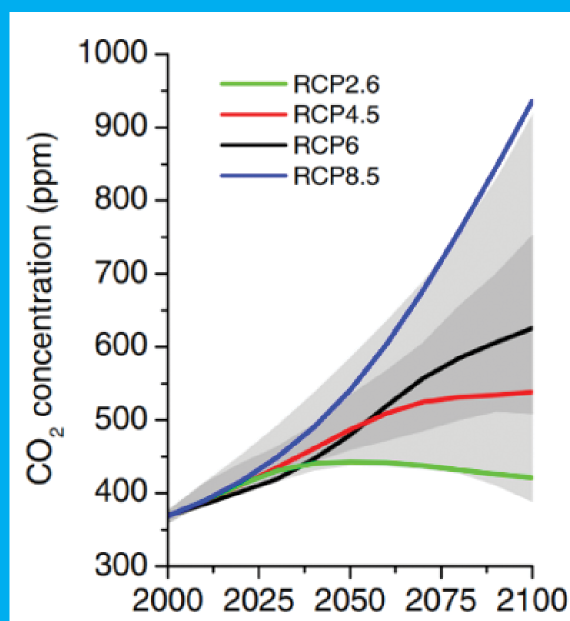
explore the RCP4.5 scenario in this assessment, and the United Nations Paris Agreement of 2016 curbs emissions at a level between RCP2.6 and RCP4.5.

- RCP6.0.—A second stabilization scenario, but in this pathway greenhouse gas emissions peak at 2080 and stabilization is not achieved until after 2100 (Fujino et al. 2006).
- RCP8.5.—The business-as-usual emission scenario where greenhouse gas emissions increase throughout the 21st century (Riahi et al. 2007, 2009), based on the assumption that society is largely unsuccessful in curbing those emissions. We use the RCP8.5 scenario, in which greenhouse gases steadily rise, and note that this pathway best matches current trends.

Representative Concentration Pathways

Representative Concentration Pathways (RCPs) make different assumptions about energy sources, population growth, economic activities, and technological advancements. Scientists run general circulations models against these scenarios to project future climate conditions, including atmospheric carbon concentrations.

For this Montana Climate Assessment, we considered the stabilization (RCP4.5) and business-as-usual (RCP8.5) emission pathways.



This graph illustrates the different atmospheric CO_2 concentrations associated with each Representative Concentration Pathways. For example, if we continue our carbon emissions at the current rate (i.e., the business-as-usual [RCP8.5] emission scenario), the atmospheric CO_2 concentration will be roughly 700 ppm by 2075 (IPCC 2014).

For the Montana Climate Assessment, we explore the RCP4.5 and RCP8.5 scenarios only. We do not include RCP6.0 or RCP2.6 in our assessment for several reasons. RCP6.0 overlaps with RCP4.5 in the first half of the century and provides intermediate values between RCP4.5 and RCP8.5 at the end of the century. Additionally, RCP2.6 is becoming less and less realistic as society continues with business as usual regarding greenhouse gas emissions. For the remainder of the chapter, we will regularly refer to RCP4.5 and RCP8.5 as the stabilization and business-as-usual emission scenarios, respectively.

Due to their complexity and global extent, GCMs can be computationally intensive. Thus, scientists often make climate projections at coarse spatial resolution where each projected data point is an average value of a grid cell that measures hundreds of miles (kilometers) across.

For areas where the terrain and land cover are relatively homogenous (e.g., an expanse of the Great Plains), such coarse grid cells may be adequate to capture important climate processes. But in areas with complex landscapes like Montana, data points so widely spaced are inadequate to reflect variability in terrain and vegetation and their influence on climate. A 100 mile (161 km) grid, for example, might not capture the climate effects of a small mountain range rising out of the eastern Montana plains or the climate differences between mountain summits and valleys in western Montana where temperature and precipitation vary greatly.

To capture such important terrain characteristics, scientist take the coarse-resolution output from a GCM and statistically attribute the results from those models to smaller regions at higher resolution (e.g., grid points at 1 mile rather than 100 mile apart). This process, called downscaling, more accurately represents climate across smaller, more complex landscapes, including Montana.

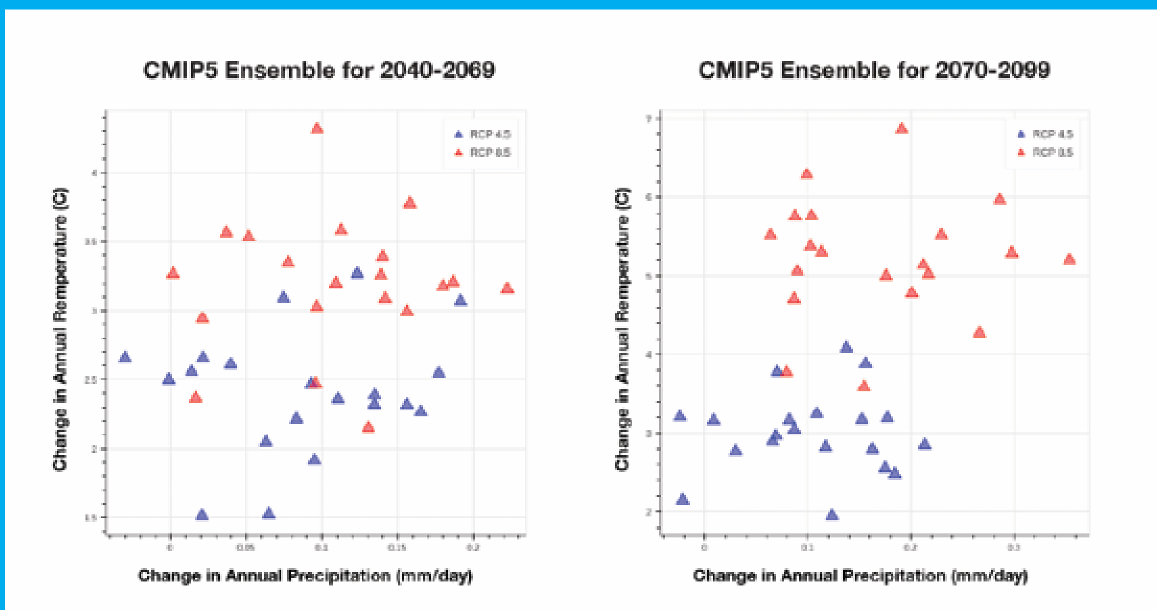
For this climate assessment, we used a statistical downscaling method called the Multivariate Adaptive Constructive Analogs.[10] By using a downscaled dataset—rather than the original output from the ensemble of GCMs—we gained the ability to evaluate temperature and precipitation at relatively high resolution statewide before conveying the results at the climate division scale. Additionally, we were able to aggregate data points within each of Montana's seven climate divisions (Figure 2-3), and look at Montana's climate future in different geographic areas. Aggregating to the climate-division level minimizes the potential for false precision by reporting results at spatial scales that better represent underlying climate processes.

The 20-downscaled GCMs in CMIP5 were evaluated at two future time periods: 1) mid century (2040–2069) and 2) end-of-century (2070–2099). Thirty-year averages of these future projections were then compared to a historical (1971–2000) 30-year average, which results in a projected difference, or change, from historical conditions. We make those projections using the stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios described previously (see sidebar). These future projections were then compared to the historical trends in Montana to reveal the major climate-associated changes that Montana is likely to experience in the future.

[10] Further detail on our downscaling methods can be found in Appendix 2-1 on the MCA website.

Modeling Montana's Climate Future

To derive the climate projections for this assessment, we employed 20 general circulation models to consider two scenarios of global carbon emissions: one where atmospheric greenhouse gases are stabilized by the end of the century and the other where it grows on its current path (the stabilization [RCP4.5] and business-as-usual [RCP8.5] emission scenarios, respectively).



Model output summary from the 20 GCMs that compares projected changes in temperature and precipitation for the state of Montana for stabilization (RCP4.5 – blue symbols) and business-as-usual (RCP8.5 – red symbols) emission scenarios between (A) mid century (2040-2069), and (B) end-of-century (2070-2099).

As shown in the figures above, we forecast Montana's future climate for two periods: mid century and end-of-century. In brief:

- *All models and scenarios show increasing annual temperatures, while most models also show increasing annual precipitation.*

- *The business-as-usual emission scenario consistently projects warmer temperatures and generally wetter conditions than the stabilization emission scenario.*
- *The end-of-century period also projects warmer temperatures but similar precipitation change to the mid-century projections. This finding suggests that temperatures will continue to warm throughout the century, but precipitation changes may level off in the latter half of the century.*

Temperature projections

Below we provide projections for various aspects of Montana's future temperature based on our modeling analysis. These projections are for the stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios and for two periods: mid century (2040-2069) and end-of-century (2070-2099).

We discuss a subset of our modeling results here, including a) temperature projections reported by the median values of the 20 GCM ensemble and b) figures that include maps and graphs that represent the median value and distribution of values observed for temperature across the 20 GCMs.

An ensemble minimum, maximum, and percent agreement are also provided parenthetically. The percent agreement represents the number of GCMs that project the same sign of change (i.e., positive or negative) as the median value. For example, if the median value is positive and 18 out of 20 models also project positive change, then the percent agreement would be 100 x 18/20 = 90%. This simple calculation helps convey the uncertainty in the projections.

Average annual temperatures

Average annual temperatures increase in the mid-century and end-of-century projections for both stabilization and business-as-usual emission scenarios (Figures 2-9, 2-10). In the mid-century projection, most of the state has increases of about 4.5°F (2.5°C) for the stabilization emission scenario and 6.0°F (3.3°C) for the business-as-usual emission scenario. For end-of-century, statewide temperature increases by about 5.6°F (3.1°C) for the stabilization emission scenario and 9.8°F (5.4 °C) for the business-as-usual emission scenario. Although small differences exist between climate divisions, the general magnitude of these changes is consistent across the state for both emission scenarios and both time periods.

- Mid-century projection specifics.—Average annual temperatures increase by mid century in both emission scenarios (Figures 2-9 and 2-10). In the stabilization emission scenario, most of the state is projected to have increases of about 4.5°F (2.5°C) (minimum: 2.7°F [1.5°C], maximum: 6.1°F [3.4°C], percent agreement: 100%). The business-as-usual emission scenario projects larger increases in temperature of about 6.0°F (3.3°C) (minimum: 4.0°F [2.2°C], maximum: 8.2°F [4.6°C], model agreement: 100%). While small discrepancies exist between climate divisions, in general the magnitude of these changes is consistent across the state in both emission scenarios.
- End-of-century projection specifics.—Average annual temperatures increase by about 5.6°F (3.1°C) (minimum: 3.6°F [2.0°C], maximum: 7.7°F [4.3°C], percent agreement: 100%) in the stabilization emission scenario and by about 9.8°F (5.4°C) (minimum: 6.6°F [3.7°C], maximum: 12.9°F [7.2°C], percent agreement: 100%) in the business-as-usual emission scenario (Figure 2-9).

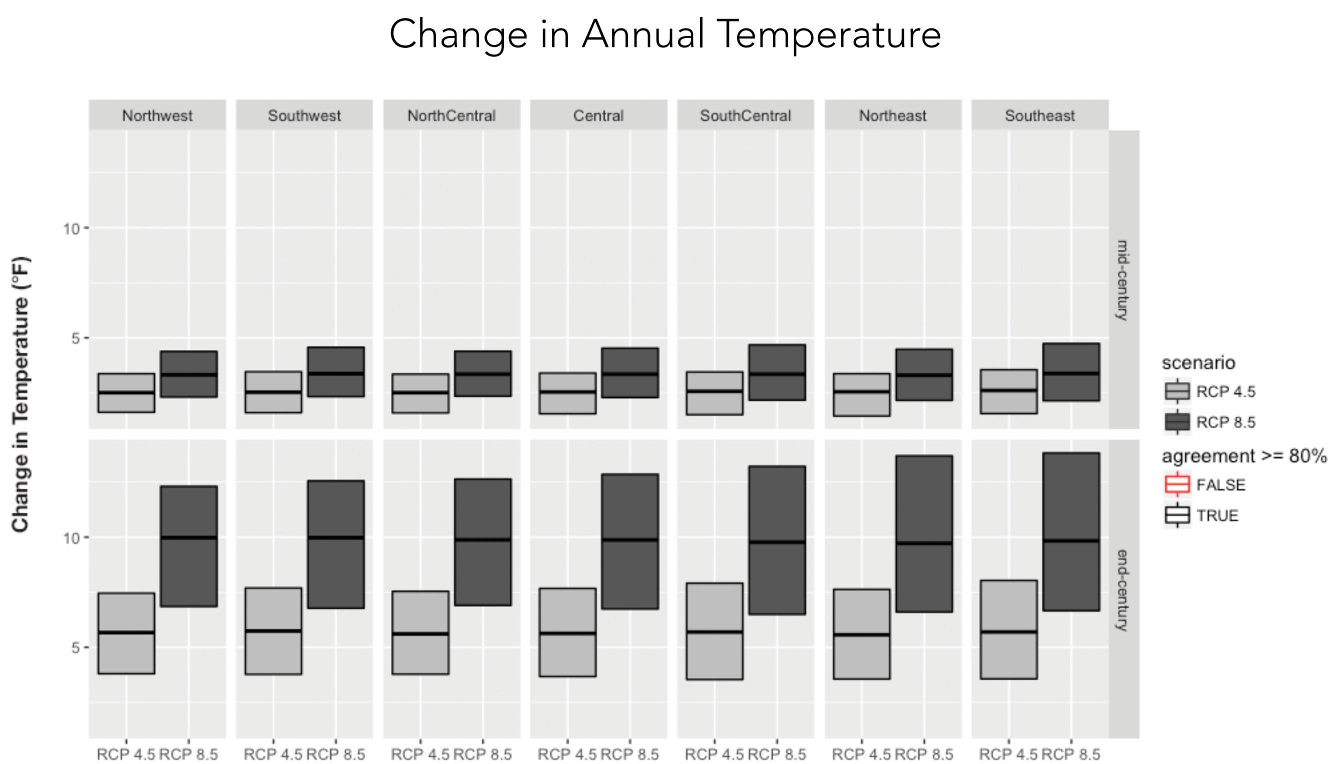


Figure 2-9. Graphs showing the minimum, maximum, and median temperature increases (°F) projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century (2040-2069) projections and the bottom row shows end-of-century (2070-2099) projections. The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement. In this case, all models indicated the direction of the temperature trend at an agreement of greater than 80%.

Average daily minimum and maximum temperatures

Average daily minimum and maximum temperatures increase in the mid-century and end-of-century projections for both stabilization and business-as-usual emission scenarios (Figure 2-10 shows output for annual average daily maximum temperature). The degree of change is similar to that found for the average annual temperatures. In end-of-century projections, summers have the largest increases in average temperature: 6.5°F (3.6°C) for the stabilization emission scenario, 11.8°F (6.6°C) for the business-as-usual emission scenario.

- Mid-century projection specifics.—Average daily minimum and maximum temperatures change in a manner similar to the average annual projected increases (again for both RCP scenarios).
- End-of-century projection specifics.—Average daily minimum and maximum temperatures increase by similar magnitudes to average annual daily temperatures for both emission scenarios. Summer months have the largest projected increase in average temperature. In the stabilization emission scenario, summer temperatures increase by 6.5°F (3.6°C) (minimum: 3.2°F [1.8°C], maximum: 9.1°F [5.1°C], percent agreement: 100%) and in the business-as-usual emission scenario, summer temperatures increase by about 11.8°F (6.6°C) (minimum: 8.0°F [4.4°C], maximum: 15.2°F [8.4°C], percent agreement: 100%).

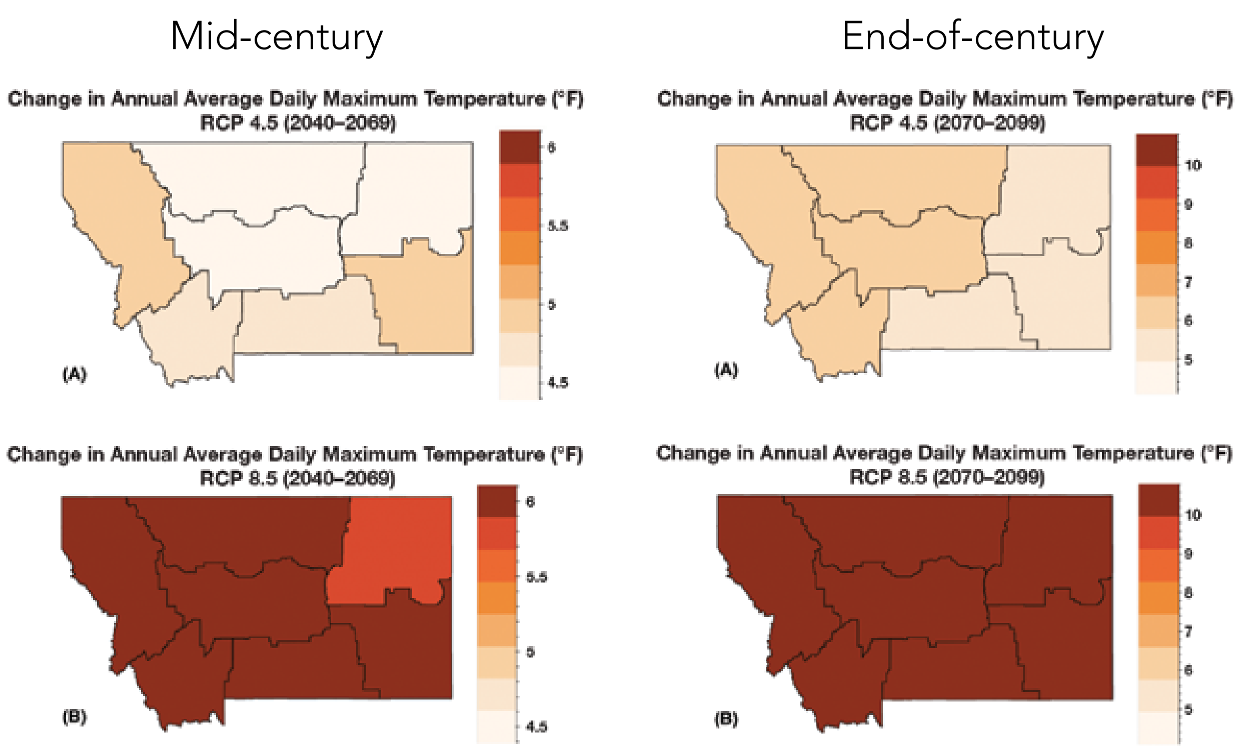


Figure 2-10. The projected increase in annual average daily maximum temperature (°F) for each climate division in Montana for the periods 2049-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

Average monthly temperatures

Average monthly temperatures are projected to increase across all climate divisions by mid century (2040-2069) and for both stabilization and business-as-usual emission scenarios (Figure 2-11). Average monthly temperatures in summer and winter generally show larger projected increases than those in spring and fall. In the business-as-usual emission scenario, August has the largest projected change across all climate divisions.

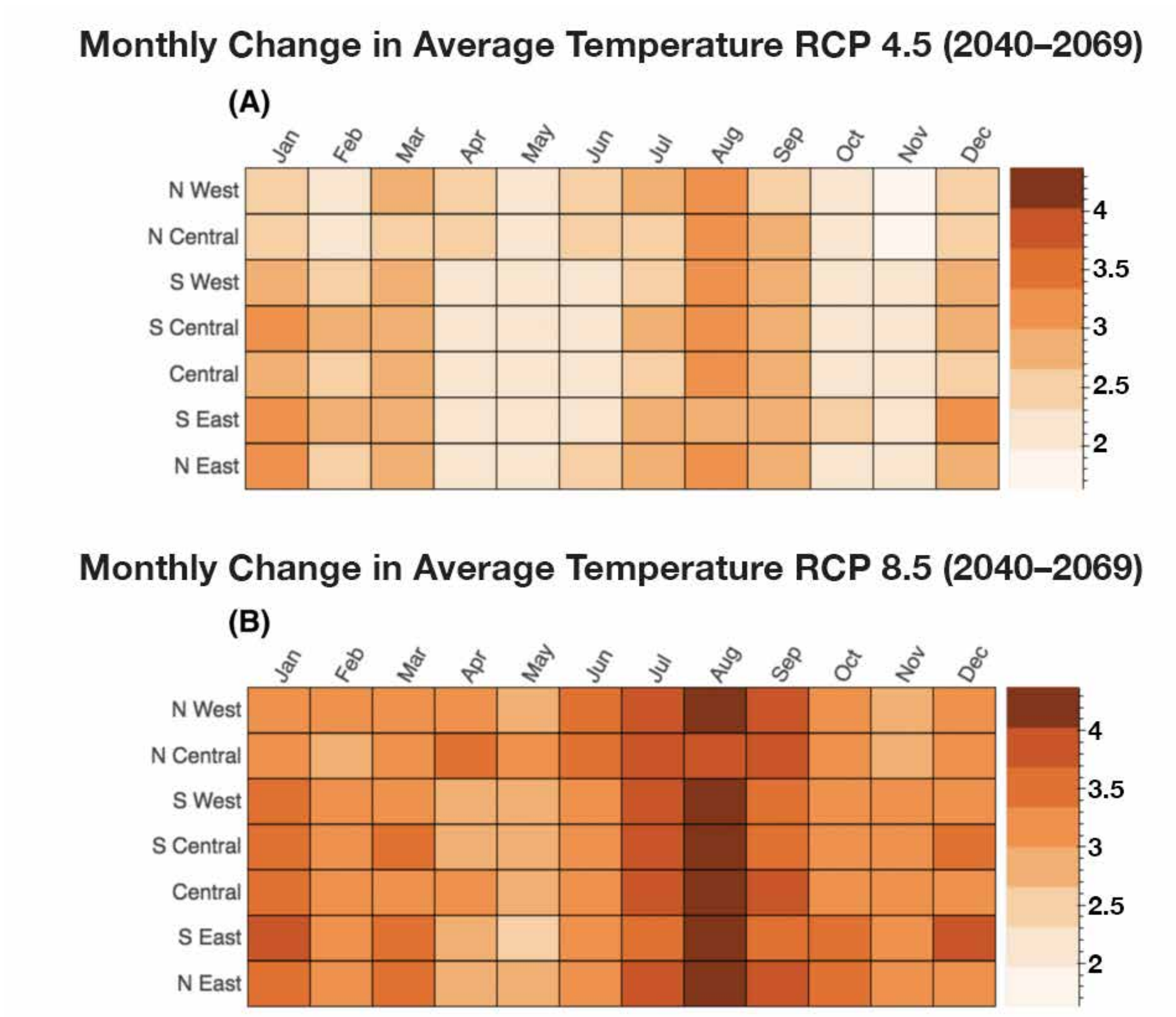


Figure 2-11. The projected monthly increase in average temperature (°F) for each climate division in Montana in the mid-century projections (2040-2069) for the (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

The number of days above 90°F (32°C)

The number of annual days where maximum temperatures are above 90°F (32°C) increases across all climate divisions in both mid-century and end-of-century projections and for both stabilization and business-as-usual emission scenarios (Figures 2-12, 2-13). Large differences in the magnitude of change exist, however, among the climate divisions. For example, in mid-century projections using the business-as-usual emission scenario, the northwestern part of the state shows increases of about 11 days with temperatures above 90°F (32°C), while the eastern parts of the state have increases of about 33 days. Similarly, in end-of-century projections based on the business-as-usual emission scenario, the northwestern part of the state shows an increase of about 34 days, while the eastern parts of the state have an increase of about 54 days above 90°F (32°C).

- Mid-century projection specifics.—The number of annual days at mid century where maximum temperatures are above 90°F (32°C) increases across all climate divisions and both emission scenarios (Figure 2-12, 2-13). Large differences in the magnitude of change exist, however, among the climate divisions. These differences are likely due, in part, to variability in moisture availability among the climate divisions and the energy it takes to evaporate this moisture (i.e., latent heat). In the stabilization emission scenario, the northwestern and north central climate divisions have increases of about 5.0 days (minimum: 1.5 days, maximum: 12.0 days, percent agreement: 100%); while the number of days in both eastern and south central climate divisions of the state increase by about 25.0 days (minimum: 6.0 days, maximum: 36.0 days, percent agreement: 100%). Similar spatial patterns exist for the business-as-usual emission scenario, but the magnitudes of change increase along with the ranges of the ensemble minimums and maximums. In the northwestern and north central climate divisions of the state, increases of about 11 days are projected (minimum: 1.5 days, maximum: 25.0 days, percent agreement: 100%); in the south central and both eastern climate divisions increases are projected to be about 33.0 days (minimum: 11 days, maximum: 44.0 days, percent agreement: 100%).
- End-of-century projection specifics.—The number of days where maximum temperatures exceed 90°F (32°C) by the end-of-century continues to increase across the state in both emission scenarios, with 100% model agreement. The spatial pattern in the end-of-century projection is similar to that of the mid-century one (Figures 2-12, 2-13). For the stabilization emission scenario, the number of days/yr exceeding 90°F (32°C) increases in the northwestern and north central regions by about 8.5 days (minimum: 1.7 days, maximum: 22.0 days, percent agreement: 100%), while in the southern and eastern parts of the state, it increases by about 29.0 days (minimum: 11.0 days, maximum: 43.0 days, percent agreement: 100%). For the business-as-usual emission scenario, the number of days exceeding 90°F (32°C) in the northwestern and north central parts of the state increases by about 34.0 days (minimum: 9.5 days, maximum: 58.0 days, percent agreement: 100%), while in the southern and eastern parts of the state, it increases by about 54.0 days (minimum: 26.0 days, maximum: 70.0 days, percent agreement: 100%).

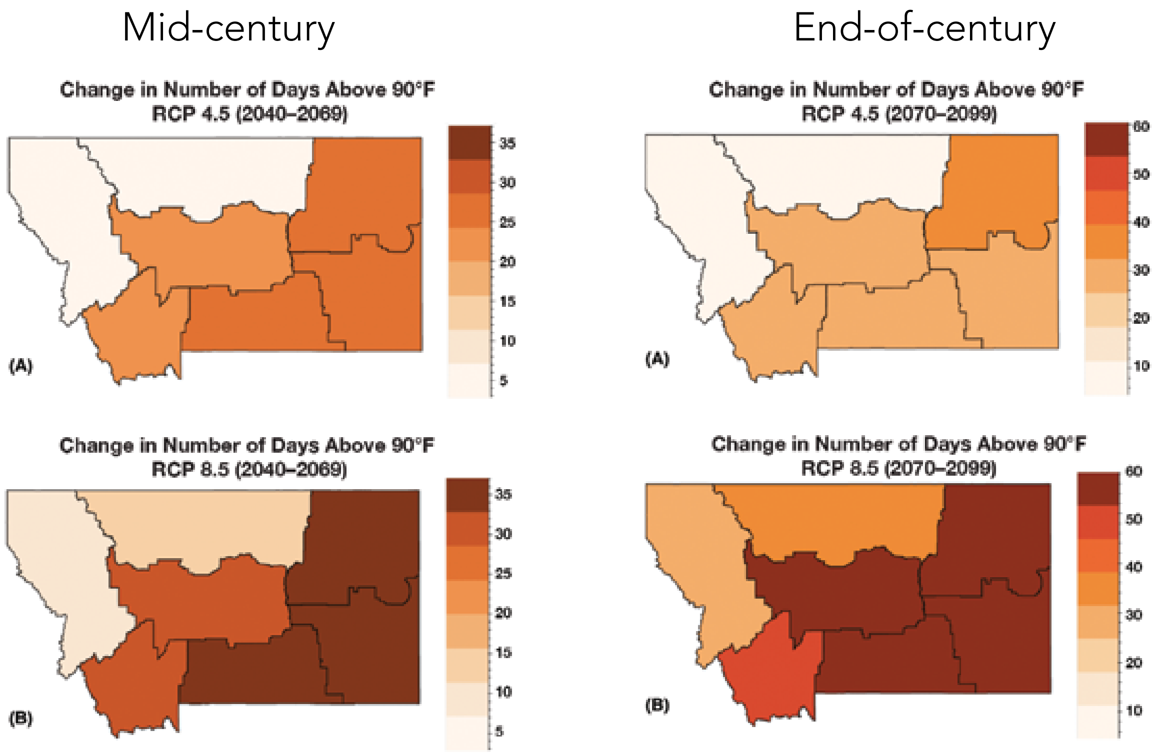


Figure 2-12. The projected increases in number of days above 90°F (32°C) for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

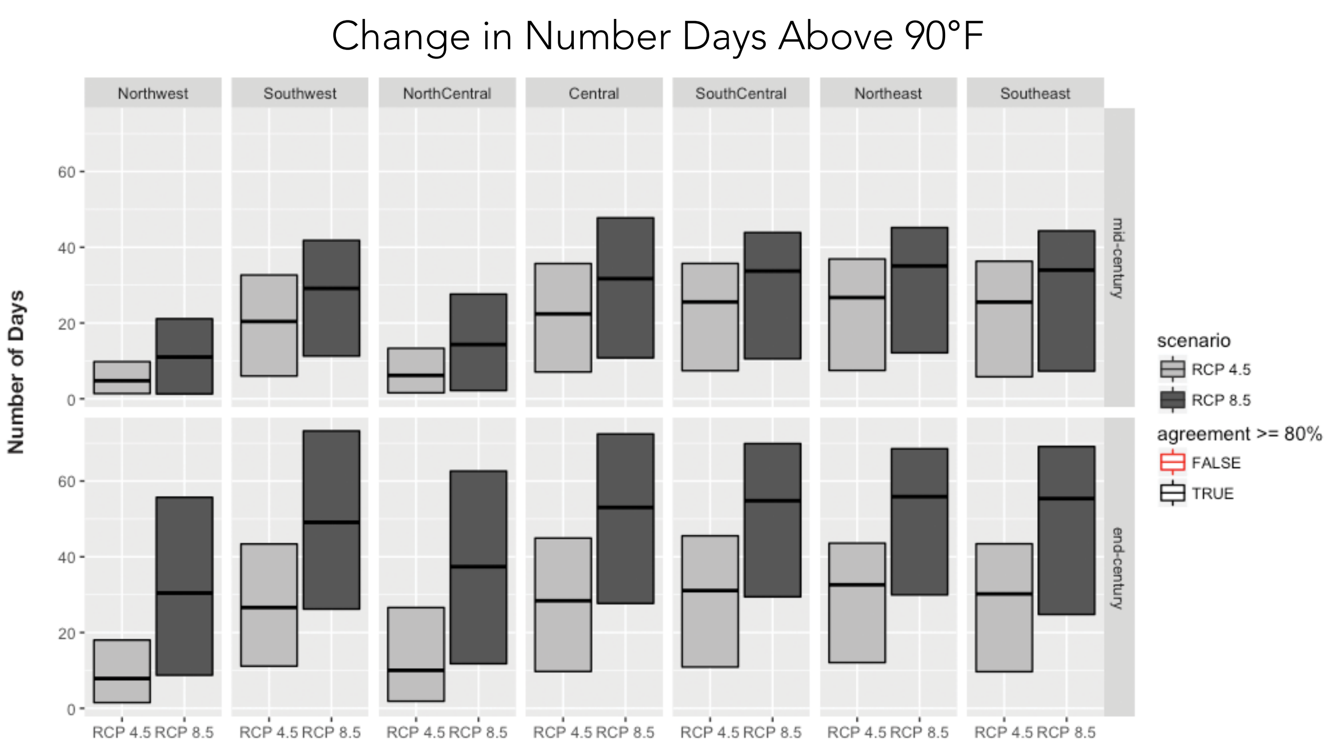


Figure 2-13. Graphs showing the increase in the number of days per year above 90°F (32°C) projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement. In this case, all models indicated the direction of the trend for days above 90°F (32°C) at an agreement of greater than 80%.

Number of days where minimum temperatures are above 32°F (0°C)

The number of days/yr where minimum temperatures exceed 32°F (0°C; i.e., frost-free days) also increases across all climate divisions in both mid- and end-of-century projections and for both stabilization and business-as-usual emission scenarios (Figures 2-14, 2-15). While varying considerably across the state, projected changes are substantial. For example, in the mid-century projections with the stabilization emission scenario, frost-free days increase by about 30 days in the western part of the state and by 23 days in the eastern part of the state. Similar patterns exist for end-of-century projections: in the business-as-usual emission scenario, frost-free days increase by about 70 days in the western part of the state and by about 55 days in the eastern part of the state.

- Mid-century projection specifics.—The number of days/yr where minimum temperatures are above 32°F (0°C; i.e., frost-free days) increases across all climate divisions and both emission scenarios (Figures 2-14, 2-15). In the stabilization emission scenario, frost-free days increase by 30.0 days in the western part of the state (minimum: 9.0 days, maximum: 51.0 days, percent agreement: 100%) and by 23.0 days in the eastern part of the state (minimum: 10.0 days, maximum: 43.0 days, percent agreement: 100%). In the business-as-usual emission scenario, frost-free days increase by 41.0 days in the western part of the state (minimum: 17.0 days, maximum: 68.0 days, percent agreement: 100%) and by 32.0 days in the eastern part of the state (minimum: 15.0 days, maximum: 63.0 days, percent agreement: 100%).
- End-of-century projection specifics.—The number of days/yr where minimum temperatures are above 32°F (0°C; i.e., frost-free days) continues to increase in the end-of-century projections across all climate divisions and for both emission scenarios, with 100% model agreement. Again, similar spatial patterns exist between the mid-century and end-of-century projections (Figures 2-14, 2-15). In the stabilization emission scenario, frost-free days increase by 41.0 days in the western part of the state (minimum: 18.0 days, maximum: 66.0 days, percent agreement: 100%), and by 30.0 days in the eastern part of the state (minimum: 14.0 days, maximum: 60.0 days, percent agreement: 100%). In the business-as-usual emission scenario, frost-free days increase by 70.0 days in the western part of the state (minimum: 36.0 days, maximum: 110.0 days, percent agreement: 100%), and by 55.0 days in the eastern part of the state (minimum: 26.0 days, maximum: 100.0 days, percent agreement: 100%).

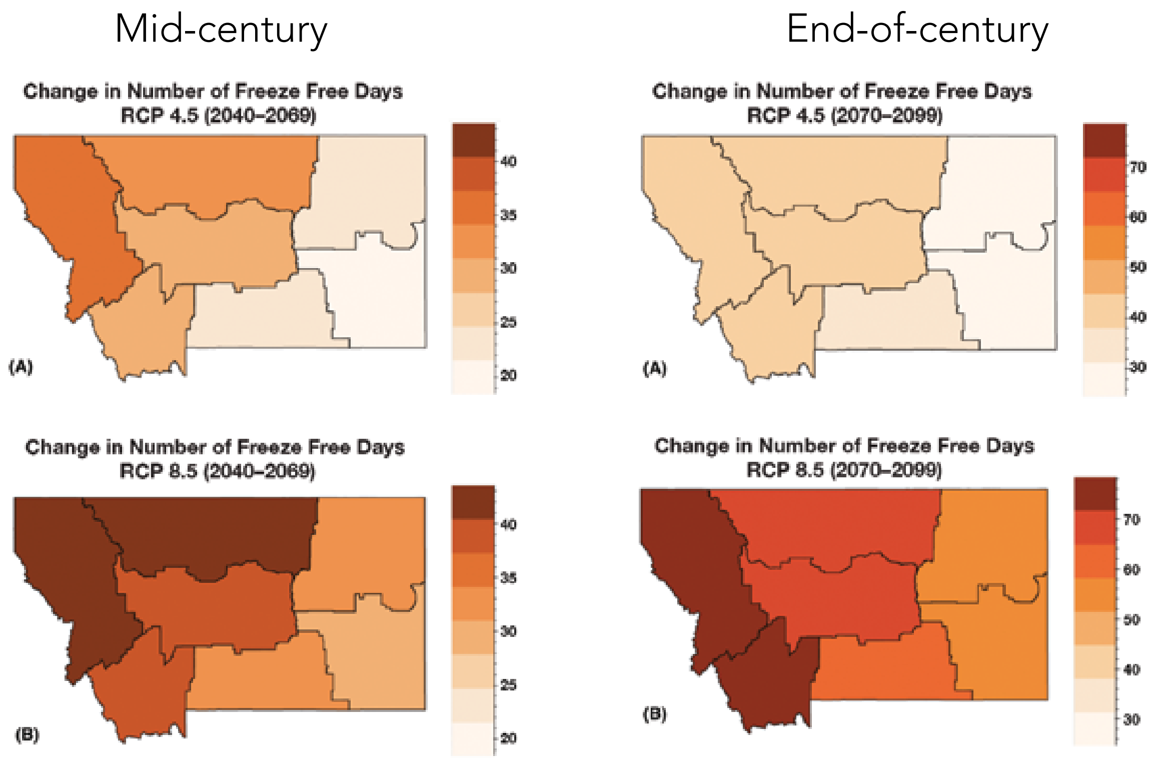


Figure 2-14. The projected change in the number of frost-free days for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

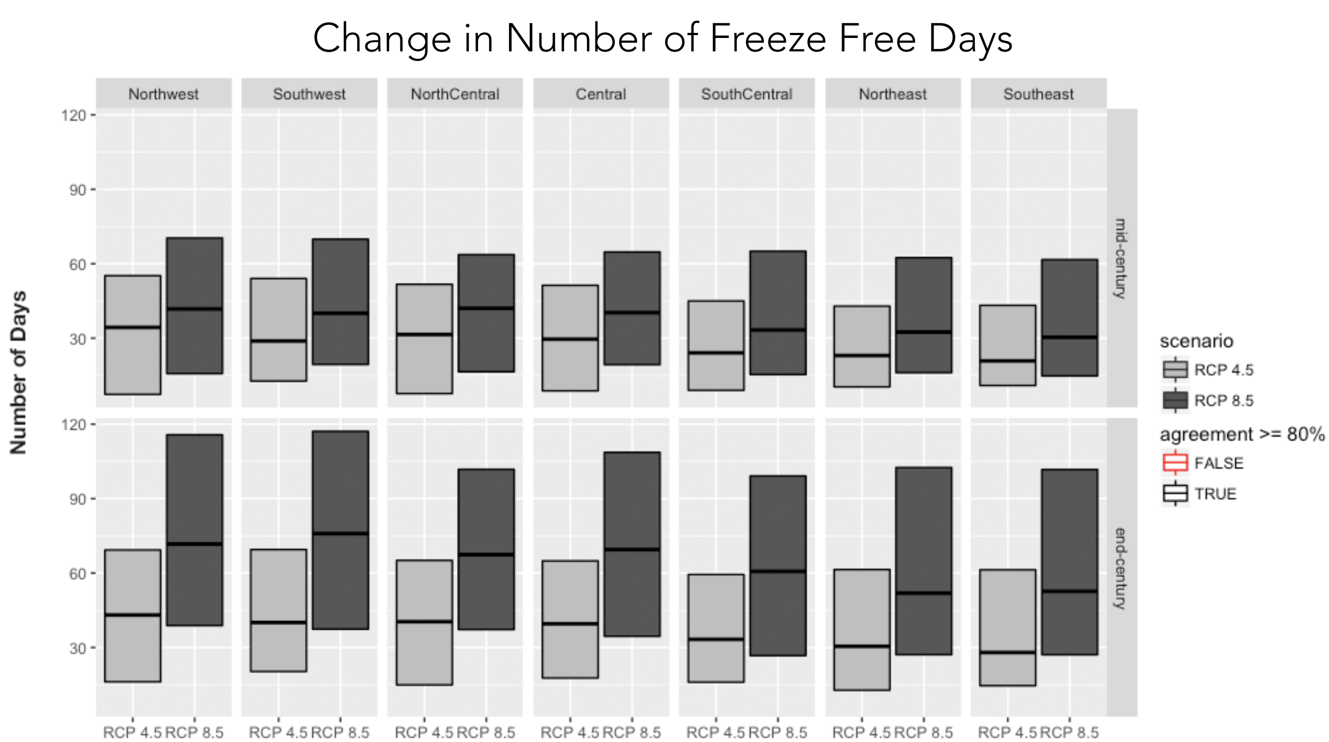


Figure 2-15. Graphs showing the increases in frost-free days/yr projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement. In this case, all models indicated the direction of the trend of frost-free days at an agreement of greater than 80%.

Summary

In general, there is high model agreement and low uncertainty that temperatures and associated temperature metrics will increase both by mid century and end-of-century. For both periods, annual and seasonal temperature averages, the number of days/yr with extreme heat, and the overall length of the growing season are projected to increase. Differences exist in projections for the stabilization and business-as-usual emission scenarios, with the former consistently showing lower magnitudes of change than the latter. Many of the trends and spatial patterns seen in the mid-century projections are extended and exacerbated in the end-of-century projections. The range of model outputs also increases for end-of-century projections, suggesting that the magnitude of change becomes more uncertain in the models further out in time.

Regardless of uncertainties, the GCMs show full agreement regarding the direction of change: temperatures will be increasing.

Precipitation projections

Below we provide projections of Montana's future precipitation based on our modeling efforts. Those projections are for the stabilization and business-as-usual emission scenarios and for two periods: mid century (2040-2069) and end-of-century (2070-2099).

We discuss a subset of our precipitation modeling results here, including a) precipitation projections reported by the median values of the 20 GCM ensemble and b) figures that include maps and graphs that represent the median value and distribution of values observed for precipitation across the 20 GCMs. Special consideration is required for interpretations of precipitation changes in Montana's complex terrain. Precipitation increases drastically with elevation such as that found in northwest Montana. Here, median values do not characterize the potential for spatial variability that exists within these regions.

An ensemble minimum, maximum, and percent agreement are also provided parenthetically. As with our temperature analysis, the percent agreement concerning the precipitation trends is based on the number of GCMs that project the same sign of change (i.e., positive or negative) as the median value. For example, if the median value is positive and 18 out of 20 models also project positive change, then the percent agreement would be 100 x 18/20 = 90%. This simple calculation helps convey the uncertainty in the projections. For some variables both the absolute change and the percent change from historical is calculated.

Average annual precipitation

Average annual precipitation increases across the state in both mid-century and end-of-century projections for both emission scenarios (Figures 2-16, 2-17, 2-18). For the mid-century projection using the stabilization emission scenario, increases of about 1.3 inch/yr (3.3 cm/yr)occur in the northwestern and north central climate divisions and about 0.9 inch/yr (2.3 cm/r) in the southwestern, central, and eastern climate divisions. For the business-as-usual emission scenario in the mid-century projection, average annual precipitation increases by about 2.0 inch/yr (5.1 cm/yr) in the western half of the state, and about 1.8 inch/yr (4.6 cm/yr) in the eastern half of the state. The GCMs used in the ensemble show large differences in their end-of-century projections, but there is high agreement in the positive direction of change.

- Mid-century projection specifics.—Average annual precipitation increases by mid century across the state for both emission scenarios, with moderately high agreement among models (Figures 2-16, 2-17, 2-18). In the stabilization scenario, increases of about 1.3 inch/yr (3.3 cm/yr) and 5.0% (minimum: -0.5 inch/yr [-1.3 cm/yr], -1.1%; maximum: 3.2 inch/yr [8.1 cm/yr], 14.0%; percent agreement: 85%) are projected in the northwestern parts of the state. In the southern and eastern parts of the state, increases of about 0.9 inch/yr (2.3 cm/yr) and 6.5% are projected (minimum: -1.2 inch/yr [-3.0 cm/yr], -6.0%; maximum: 2.5 inch/yr [6.4 cm/yr], 18.0%; percent agreement: 85%). In the business-as-usual emission scenario, average annual precipitation increase by about 1.6 inch/yr (4.1 cm/yr) and 6.5% in the northwestern parts of the state (minimum: -0.2 inch/yr [-0.51 cm/yr], -1.0%; maximum: 4.4 inch/yr [11.2 cm/yr], 17.0%; percent agreement: 90%), and by about 1.2 inch/yr (3.0 cm/yr) and 10% in the southern and eastern parts of the state (minimum: -0.5 inch/yr [-1.3 cm/yr], -3.5%; maximum: 2.9 inch/yr [7.4 cm/yr], 22.0%; percent agreement: 85%).
- End-of-century projection specifics.—Average annual precipitation is projected to increase through the end-of-century for both emission scenarios (Figures 2-16, 2-17, 2-18). The GCMs used in the ensemble show large differences in their end-of-century projections, but there is high agreement in the positive direction of change. In the stabilization emission scenario, average annual precipitation increases in the northwestern climate division by about 2.2 inch/yr (5.6 cm/yr) and 7.3% (minimum: -1.2 inch/yr [-3.0 cm/yr], -4.5%; maximum: 3.6 inch/yr [9.1 cm/yr], 12.9%; percent agreement: 85%), and by about 1.1 inch/yr (2.8 cm/yr) and 8.0% in the two eastern climate divisions (minimum: -0.5 inch/yr [-1.3 cm/yr], -4.5%; maximum: 3.0 inch/yr [7.6 cm/yr], 18.0%; percent agreement: 85%). In the business-as-usual emission scenario, average annual precipitation is projected to increase by slightly more than in the stabilization emission scenario, although the range of model projections also increases. In the western half of the state, annual precipitation increases by about 2.0 inch/yr (5.1 cm/yr) and 10.0% (minimum: 0.4 inch/yr [1.0 cm/yr], 1.3%; maximum: 5.5 inch/yr [14.0 cm/yr], 28.0%; percent agreement: 100%), and in the eastern half of the state annual precipitation increases by about 1.8 inch/yr (4.6 cm/yr) and 14.0% (minimum: -0.2 inch/yr [-0.5 cm/yr], -1.0%; maximum: 3.6 inch/yr [9.1 cm/yr], 26.0%; percent agreement: 95%).

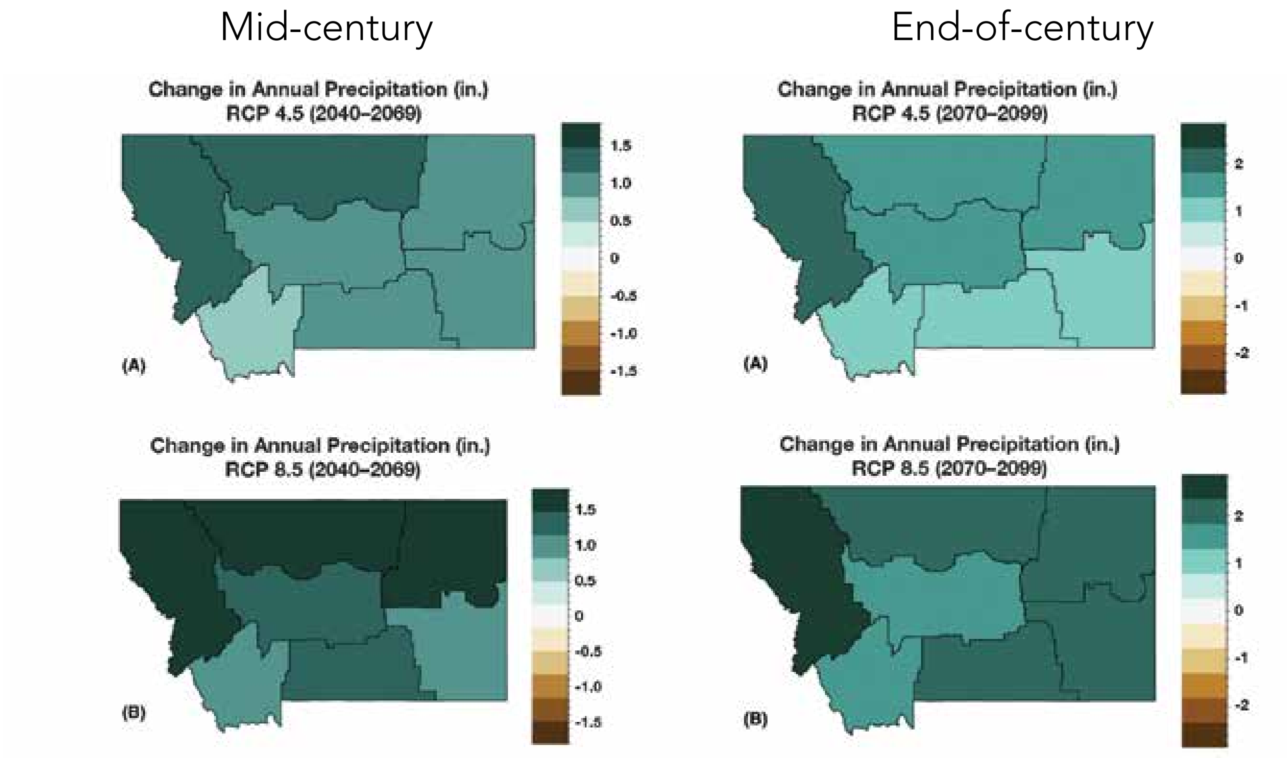


Figure 2-16. The projected change in annual precipitation (inches) for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

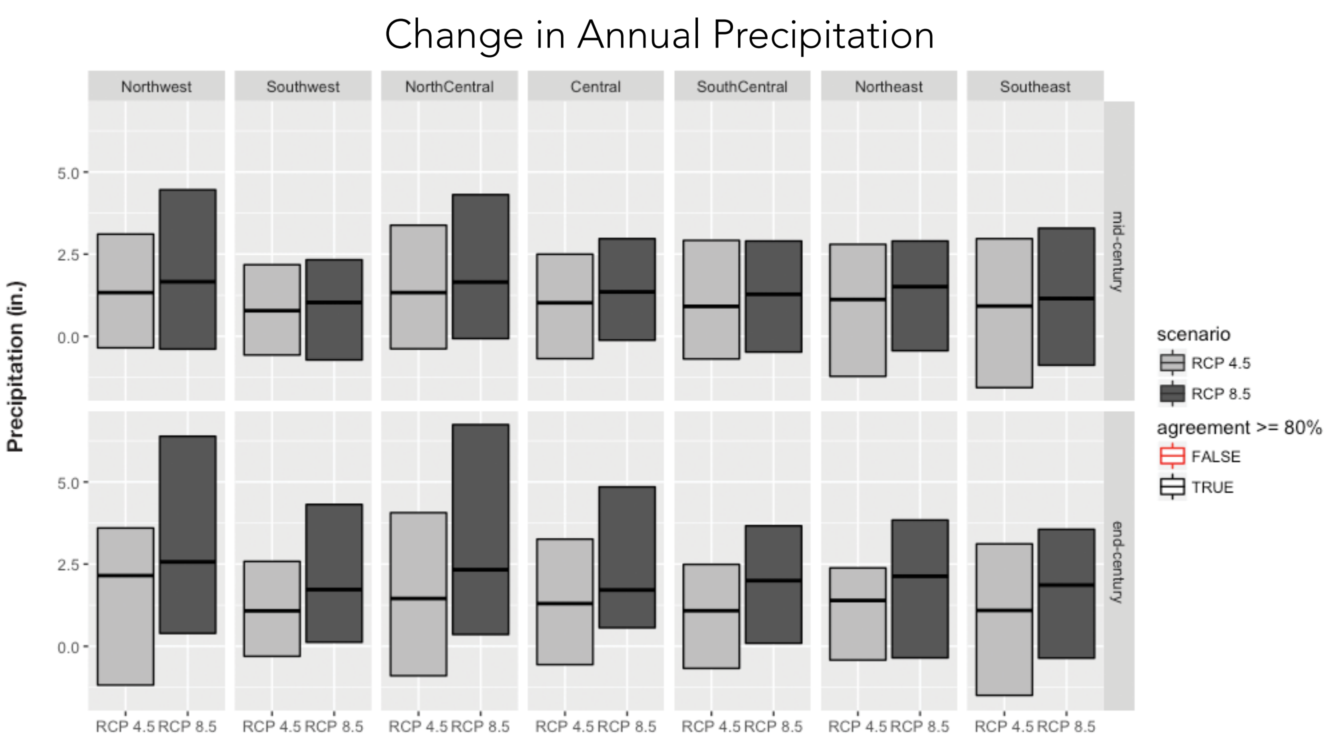


Figure 2-17. Graphs showing annual precipitation change (in inches) projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement. In this case, all models indicated the direction of the annual precipitation trend at an agreement of greater than 80%.

Change in Annual Precipitation

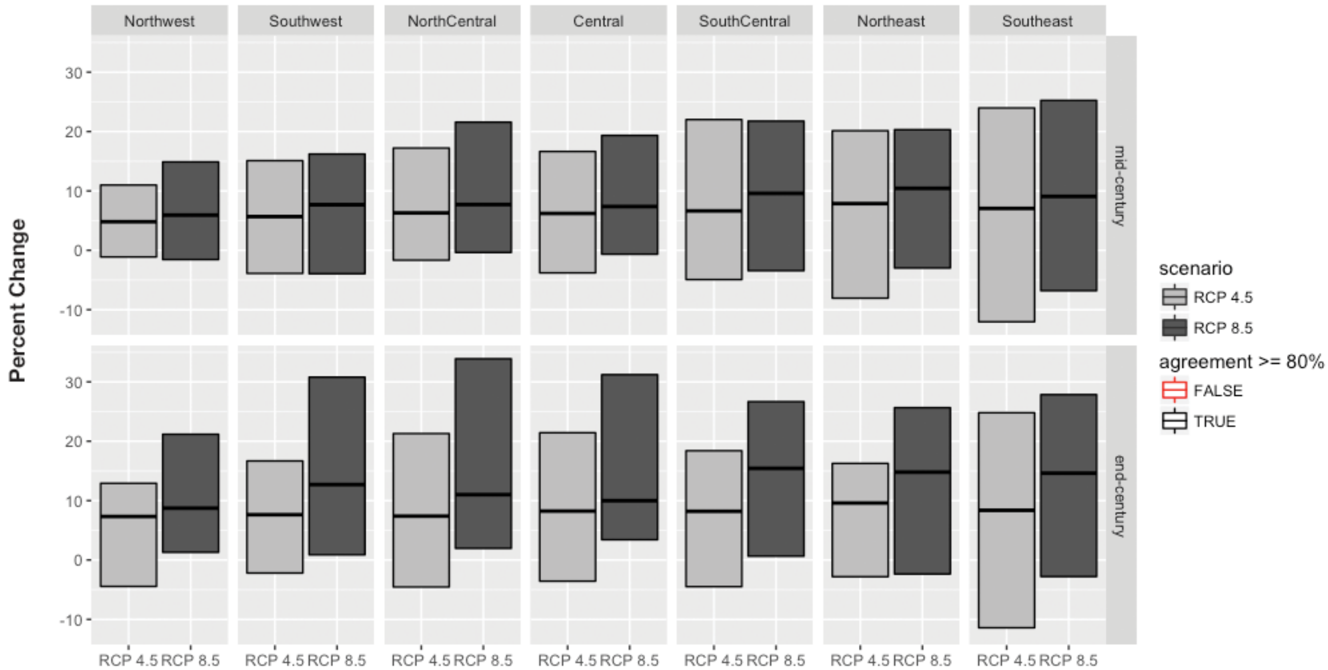


Figure 2-18. Graphs showing the minimum, maximum, and median percent changes in annual precipitation projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement. In this case, all models indicated the direction of the precipitation trend at an agreement of greater than 80%.

Interannual variability

Interannual variability (i.e., the amount precipitation changes from year to year) is also projected to increase slightly across the state by mid century and end-of-century for both emission scenarios (Figure 2-19). The increase could be attributed to wet years getting wetter, dry years getting drier, or some combination of both.

Change in Interannual Variability

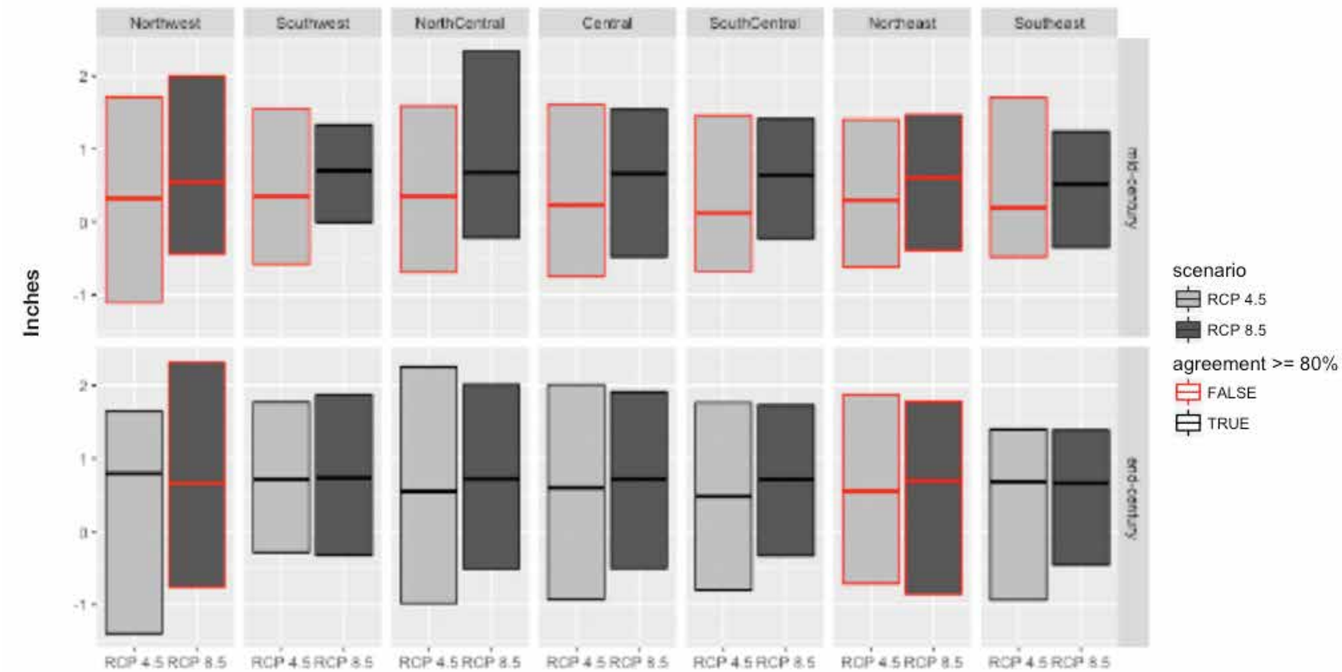


Figure 2-19. Graphs showing the interannual variability of precipitation projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows for end-of-century projections (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement.

Monthly and seasonal change in average precipitation

While annual increases in precipitation are projected across the state with moderately high model agreement, the monthly and seasonal projections vary. In mid-century projections, winter, spring, and fall increase in monthly precipitation for both emission scenarios, with spring experiencing the largest increases (e.g., 0.4 inch/month [1.0 cm/month] for the business-as-usual emission scenario; Figure 2-23). Summers, however, are projected to decrease by about 0.1 inch/month (0.3 cm/month) in both emission scenarios (model agreement, however, is fairly low for these projections). For end-of-century projections, the same trends are seen for increasing precipitation in winter, spring, and fall and decreasing precipitation in summer. The magnitude of change is similar to that of mid-century projections.

- Mid-century projection specifics.—Although annual precipitation increases across the state with moderately high model agreement, the monthly and seasonal projections vary somewhat. Winter, spring, and fall increase in monthly precipitation for both emission scenarios, with the largest increases in spring (Figure 2-20). For the stabilization emission scenario, spring months increase by about 0.2 inch/month (0.5 cm/month) (minimum: -0.1 inch/month [-0.3 cm/month], maximum: 0.8 inch/month [2.0 cm/month], percent agreement: 85%). In the business-as-usual emission scenario, spring months increase by 0.4 inch/month (1.0 cm/month) (minimum: 0.0 inch/month [0 cm/month], maximum: 1.0 inch/month [2.5 cm/month], percent agreement: 95%). Summer months, however, show decreasing precipitation for both scenarios, although model agreement is fairly low in the projections. For the both the stabilization and business-as-usual emission scenarios, summer precipitation decreases by -0.1 inch/month (-0.3 cm/month) (minimum: -0.4 inch/month [-1.0 cm/month], maximum: 0.5 inch/month [1.3 cm/month], percent agreement: 65%).

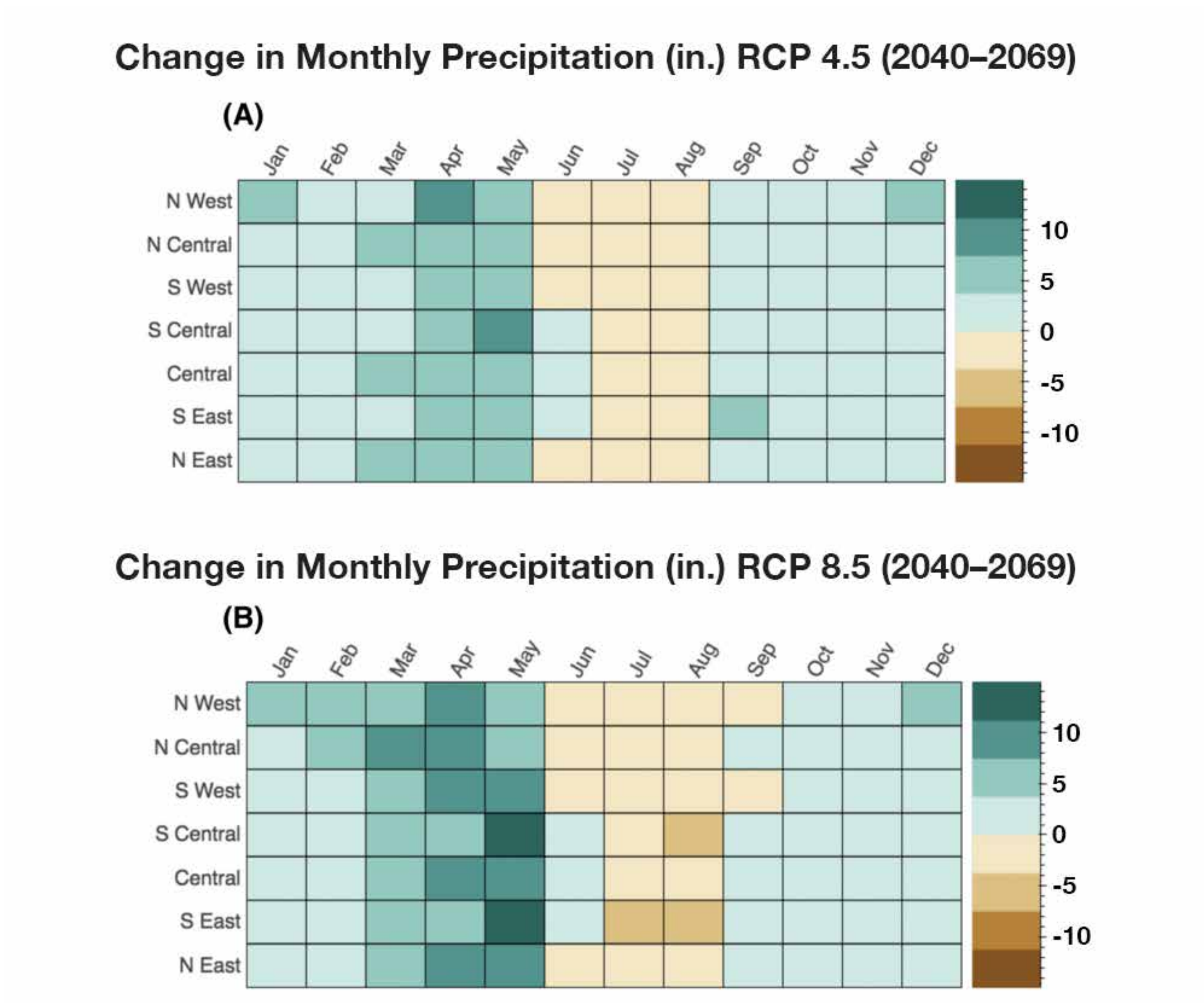


Figure 2-20. Projected monthly change in average precipitation (inches) for each climate division in Montana in the mid-century projections (2040-2069) for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

- End-of-century projection specifics.—Across the state and for both emission scenarios, the trend of increasing precipitation in winter, spring, and fall continues in the end-of-century projections. The trend in decreasing summer precipitation also continues (Figure 2-21). For both the stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios, spring has the largest projected changes in seasonal precipitation with increases of 0.4 inch/month (1.0 cm/month) (minimum: -0.1 inch/month [-0.3 cm/month], maximum: 1.1 inch/month [2.8 cm/month], percent agreement: 85%). In the summer months, projected precipitation is less than historical, but similar to mid-century levels. For the stabilization and business-as-usual emission scenarios, summer precipitation is projected to decrease by -0.2 inch/month (-0.5 cm/month) (minimum: -0.5 inch/month [-1.3 cm/month], maximum: 0.5 inch/month [1.3 cm/month], percent agreement: 75%).

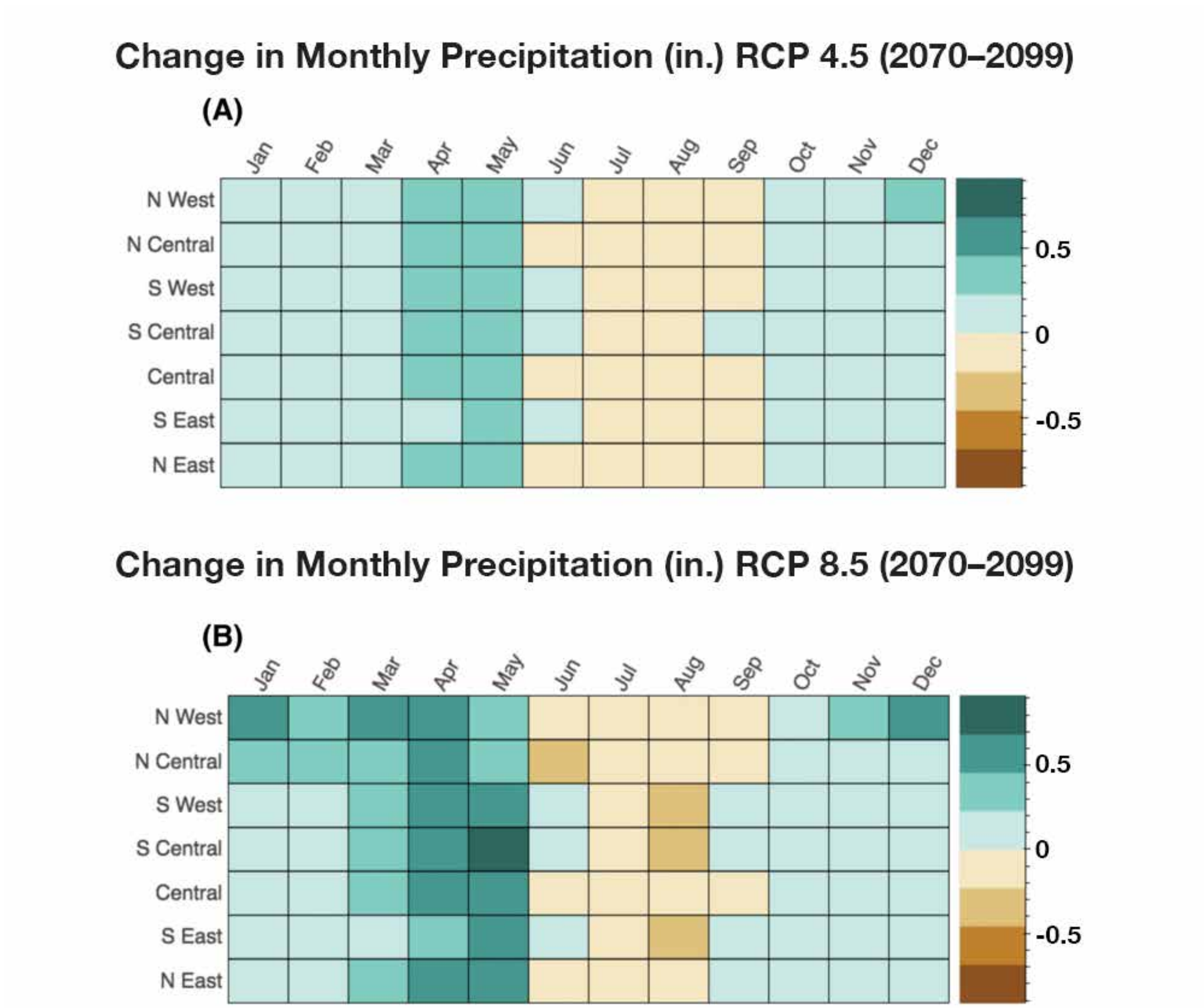


Figure 2-21. The projected monthly change in average precipitation (inches) for each climate division in Montana in the end-of-century projections (2070-2099) for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

Projected change in consecutive dry days

To assess changes in the frequency of dry events, we determined the annual number of dry days (defined as days when precipitation is less than 0.01 inch [0.03 cm]), then calculated the maximum number of consecutive dry days/yr averaged over the 30-year periods of interest. In general, in both mid- and end-of-century projections, we found a modest increase statewide in consecutive dry days—generally less than 0.5 days—for both emission scenarios (Figures 2-22, 2-23). Low model agreement exists and the range of projections from the ensemble of GCMs is wide, both suggesting high uncertainty in these projections.

- Mid-century projection specifics.—In general, consecutive dry days show a modest increase (i.e., less than 0.5 days); however, model agreement is low (approximately 60%; where 50% would mean complete disagreement among models) in both emission scenarios.
- End-of-century projection specifics.—In end-of-century projections, changes in consecutive dry days/yr remain positive, but the increase is small (generally less than 0.5 days) with low model agreement (approximate 60%). This result is consistent across both emission scenarios. The range of projections from the ensemble of models is wide; however, minimum and maximum values are projected to increase by about -2.5 days and 4.0 days, respectively. This large range, in addition to the low model agreement, suggests high uncertainty in these projections.

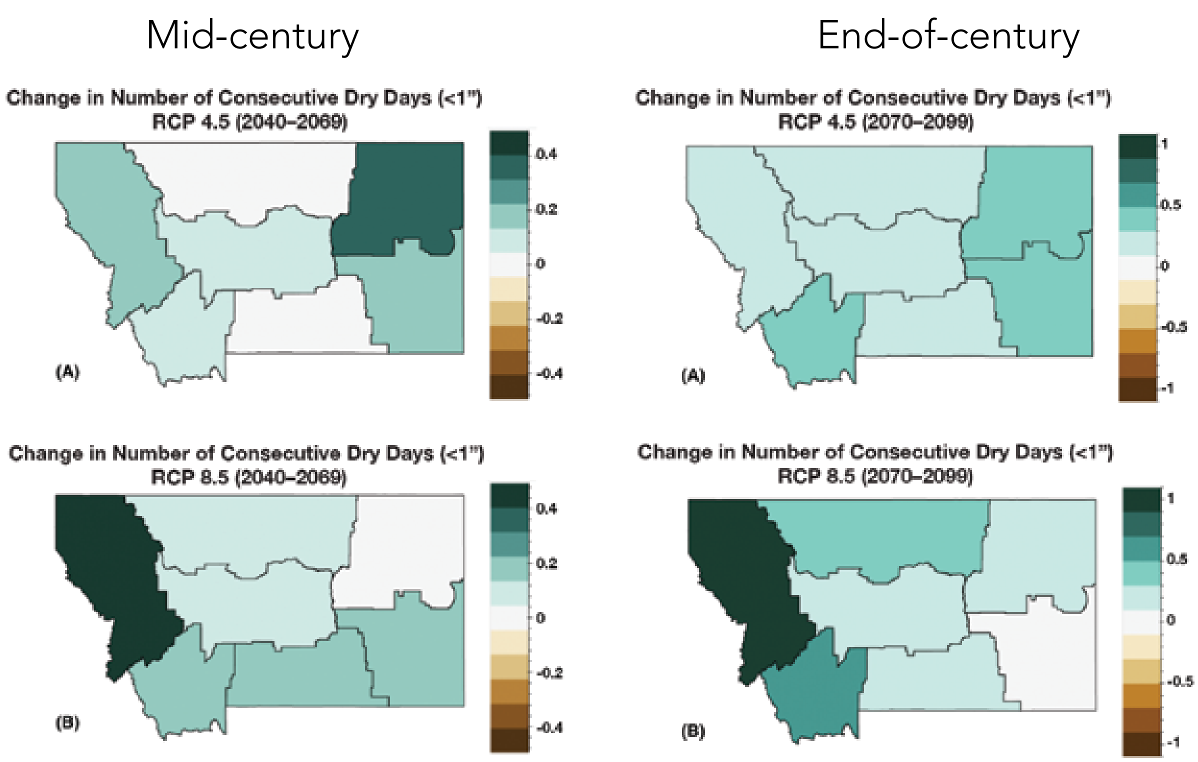


Figure 2-22. The projected change in the number of consecutive dry days (<0.1 inch [0.3 cm] of precipitation) for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

Change in Number of Consecutive Dry Days

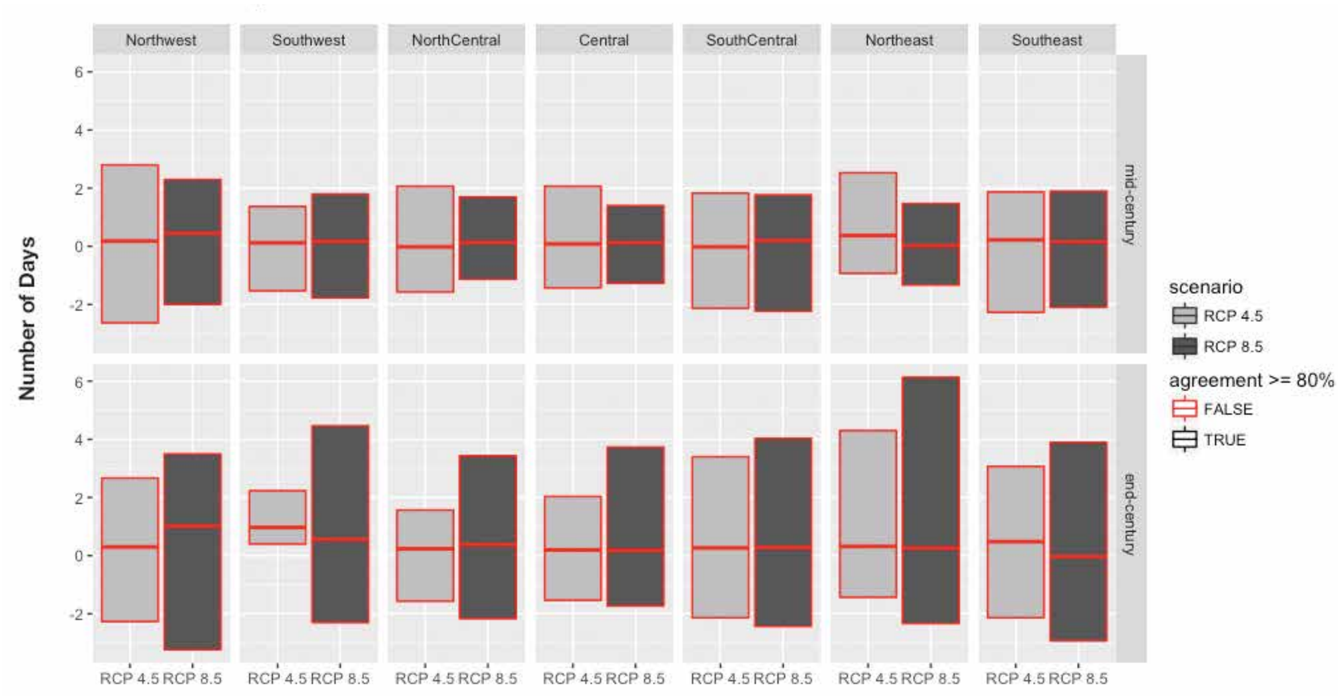


Figure 2-23. Graphs showing the number of consecutive dry days in a year projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline means that there is <80% model agreement. In the case of consecutive dry days, there was less than 80% agreement across the models for all climate divisions.

Projected change in wet days

To evaluate changes in wet events, we calculated the number of days/yr where precipitation is greater than 1.0 inch (2.5 cm) and average those values over the period of interest (Figures 2-24).

- Mid-century projection specifics.—Very modest changes in the number of wet events (i.e., less than 0.5 days) is projected for both emission scenarios. This time, however, model agreement is high that these small changes will occur (approximately 90%).
- End-of-century projection specifics.—Very high model agreement (approximately 100%) exists that the number of days/yr with precipitation above 1.0 inch (2.5 cm) will increase, although the magnitude of change is still small (less than 1.0 day). The northwestern climate division is projected to have the largest changes in this metric for both emission scenarios, reaching almost a 1.0 day increase of over 1.0 inch (2.5 cm) of precipitation for the period from 2070 to 2099. The range of model output is higher in the business-as-usual emission scenario.

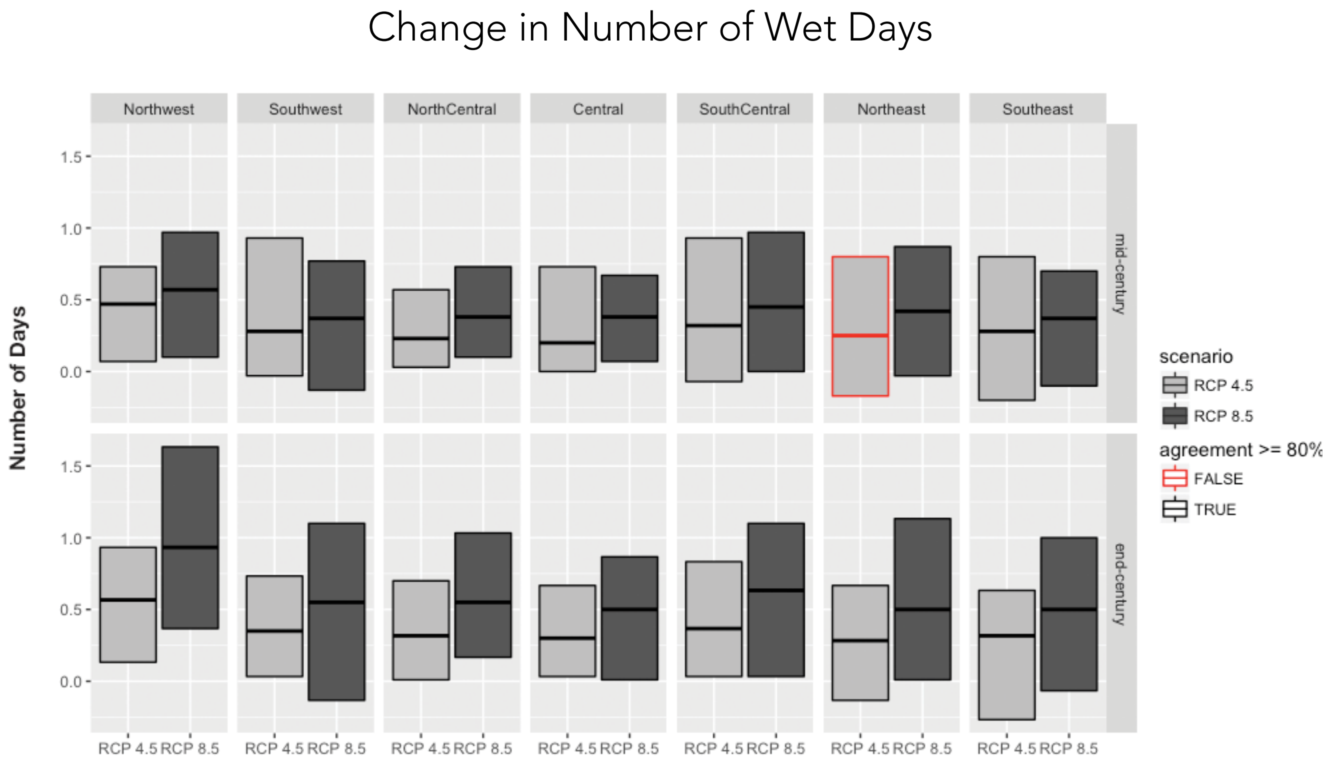


Figure 2-24. Graphs showing the increase in the number of wet days/yr projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows projections for mid century (2040-2069) and the bottom row shows projections for end-of-century (2070-2099). The outline of each box is determined by model agreement on the sign of the change (positive or negative). A black outline means there is >=80% model agreement and a red outline indicates <80% model agreement. Model agreement for the trend of wet days each year was greater than 80%, except for the northeastern climate division.

Summary

In mid-century and end-of-century projections, average annual precipitation and variability increase across the state, as does winter, spring, and fall precipitation. Summers, however, show slight decreases in precipitation. The projections suggest little change in the annual frequency of dry and wet events, although there is high uncertainty in the case of wet events. Similar analysis using different metrics for the larger region surrounding Montana indicates an even larger potential (30%) for more days of extreme precipitation (NCA 2014). Overall, the differences in precipitation resulting from the different emission scenarios (i.e., stabilization versus business-as-usual) are small when compared to the impact of the emission scenarios on the temperature projections. Uncertainty in the projections generally increases the further out in time (i.e., in the end-of-century projections), as well as for the higher business-as-usual emission scenario.

KEY KNOWLEDGE GAPS

1 Additional climate variables.—Our analysis provides a critical local look at changes for two important climate variables, precipitation and temperature. However, Montana's climate and its impacts go beyond these. A more in depth downscaling effort that involves physics based models will be required to evaluate two additional important variables, evapotranspiration and drought.

2 Land use and land cover change.—Most climate analyses do not account for changes in land cover with climatic trends. However, interactions between climate, vegetation cover, and land use quality are tightly coupled. For example, with changes in temperature and precipitation, ecosystems within Montana may shift to drier conditions resulting in changes to vegetation types. This would contribute to a difference in evapotranspiration rates and aridity.

3 Precipitation timing and form.—We took a first look at changes in Montana's precipitation. However, it is well known that the timing (winter versus spring and summer) and form (rain versus snow) of Montana's precipitation is critical for areas such as water, forests, and agriculture resources. More work that incorporates physically based, distributed hydrological models is required to understand how our precipitation distribution will change in both space (low elevations to mountaintops) and time.

CONCLUSIONS

The analysis presented in this chapter shows that Montana has warmed—up to 2.7°F (1.5°C) annually as averaged across the state—since 1950. Seasonally, that warming has been greatest in winter (3.9°F [2.2°C]) and spring (2.6°F [1.4°C]). Montana's number of frost days has decreased by 12 days since 1951. Statewide, average annual precipitation did not change between 1950 and 2015, although variations caused by global climate oscillations, such as El Niño events, explain some of the historical precipitation variability in parts of the state.

With this historical context, we considered Montana's future under two potential greenhouse gas emission scenarios. Using those scenarios, we employed standard modeling techniques available to climate scientists today—ensembles of general circulation models—and projected Montana's climate over the next century. Our analyses focused on projecting the possible range of temperature and precipitation amounts in Montana, under our chosen greenhouse gas emission scenarios.

While the model results varied, one message is imminently clear: *Montana in the coming century will be a warmer place.*

One thing is clear: Montana in the coming century will be a warmer place.

In Table 2-6 we provide a summary of the work done and described in this chapter (plus in accompanying appendices). In summary, Montana is projected to continue to warm in all geographic locations, seasons, and under all emission scenarios throughout the 21st century. By mid century, Montana temperatures are projected to increase by up to 6°F (3°C); by the end of the century, temperatures will increase by up to 9.8°F (5.4°C) (both projections depend on the particular carbon emission scenario [i.e., RCP], and these numbers are based on the business-as-usual [RCP8.5] scenario). Projections show that we could have up to 70 more frost-free days at the end of the century. Likewise, frequency of extreme heat will increase. In eastern Montana, for example, we may have as many as 54 days/yr in which maximum temperatures exceed 90°F (32°C).

In mid- and end-of-century projections, average annual precipitation and variability increase across the state, as do winter, spring, and fall precipitation. Summer months, however, show small decreases in precipitation. Current projections suggest little change in the frequency of dry and wet events, although projections in the former case show high uncertainty.

Montanans must be prepared for projected increases in temperature in the future. Because of its interior location, Montana has warmed more over the last 65 yr than the national average, and it will experience greater warming than most parts of the country in the future, particularly when compared to states in coastal regions. Key to the concern is that coming temperature changes will be larger in magnitude and occur more rapidly than any time since our 1889 declaration of statehood (and, to be sure, well before).

Montana's average annual temperature is projected to increase through the end-of-century for all models, all emission scenarios, and in all geographic locations.

Changes in temperature and precipitation associated with climate change will undoubtedly impact Montana's water resources, forestry, and agriculture. These changes will have direct impacts on all Montanans, as we explore in subsequent chapters of this assessment.

Table 2-6. Summary of climate metrics described in this chapter.

Climate Metric—	Trend and future scenario
Atmospheric CO_2 concentrations	Global atmospheric carbon dioxide concentrations have increased over 100 ppm since Montana statehood and are projected to increase under both future scenarios considered here.
Average temperature	Since 1950, average statewide temperatures have increased by 0.5°F/decade (0.3°C/decade), with greatest warming in spring; projected to increase by 3-7°F (1.7-3.9°C) by mid century, with greatest warming in summer and winter and in the southeast.
Maximum temperatures	Maximum temperatures have increased most in spring and are projected to increase 3-8°F (1.7-4.4°C) by mid century, with greatest increases in August and in the southeast.
Days above 90°F (32°C)	Extreme heat days are projected to increase by 5-35 additional days by mid century, with greatest increases in the northeast and south.
Minimum temperatures	Minimum temperatures have increased most in winter and spring and are projected to increase 3-7°F (1.7-3.9°C) by mid century, with greatest increases in January and in the southeast.
Frost-free days	Frost-free days are projected to increase by 24-44 days by mid century, particularly in the west.
Average precipitation	Statewide precipitation has decreased in winter (0.14 inches/decade [-0.36 cm/decade]) since 1950, but no significant change has occurred in annual mean precipitation, probably because of very slight increases in spring and fall precipitation. Precipitation is projected to increase, primarily in spring (0.2-0.7 inches [0.5-1.8 cm]) in the northwest; a slight statewide decrease in summer precipitation and increased year-to-year variability of precipitation are projected, as well.
Number of consecutive dry days	Little projected change, with a maximum increase of 3 days to -3 days under the most severe scenario by end of the century. However, increased variability in precipitation suggests potential for more severe droughts, particularly in connection with climate oscillations.
Number of consecutive wet days	No substantial change projected.

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Cow Island of the Missouri River.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

KEY SECTOR

03. WATER AND CLIMATE CHANGE IN MONTANA

Wyatt F. Cross, John LaFave, Alex Leone, Whitney Lonsdale, Alisa Royem, Tom Patton, and Stephanie McGinnis

Water is the lifeblood of Montana. We depend on an adequate supply of clean water for nearly every aspect of our lives, including food production, hydroelectric power, domestic and industrial uses, and sustaining our treasured natural ecosystems. Water is also strongly influenced by climate, as changes in temperature and precipitation consistently alter patterns of water availability and quality throughout the state. It is thus critical that we understand the impacts of climate change on Montana's water resources. This chapter synthesizes scientific information on how climate change is influencing the supply and distribution of water in Montana. The information presented here represents an essential first step—understanding what's changing—within the longer-term, iterative process of adapting and improving our resilience to the challenges of an uncertain climate future.

KEY MESSAGES

- Montana's snowpack has declined over the observational record (i.e., since the 1930s) in mountains west and east of the Continental Divide; this decline has been most pronounced since the 1980s. *[high agreement, medium evidence]*[11]

- Warming temperatures over the next century, especially during spring, are likely to reduce snowpack at mid and low elevations. *[high agreement, robust evidence]*

- Historical observations show a shift toward earlier snowmelt and an earlier peak in spring runoff in the Mountain West (including Montana). Projections suggest these patterns are very likely to continue into the future as temperatures increase. *[high agreement, robust evidence]*

- Earlier onset of snowmelt and spring runoff will reduce late-summer water availability in snowmelt-dominated watersheds. *[high agreement, robust evidence]*

- Long-term (decadal and multi-decadal) variation in total annual streamflow is largely influenced by patterns of climate variability; the influence of climate warming on these patterns is uncertain. *[high agreement, medium evidence]*

- Total annual streamflows are projected to increase slightly for most Montana rivers, but the magnitude of change across the state and agreement among models vary. *[medium agreement, medium evidence]*

- Local responses of groundwater resources to climate change will depend on whether aquifers are directly sensitive to climate variability, are buffered from climate by water-use practices such as irrigation, or are used to meet water demands that exceed or replace surface water supplies. *[high agreement, robust evidence]*

- Groundwater demand will likely increase as elevated temperatures and changing seasonal availability of traditional surface-water sources (e.g., dry stock water ponds or inability of canal systems to deliver water in a timely manner) force water users to seek alternatives. *[high agreement, medium evidence]*

- Multi-year and decadal-scale droughts have been, and will continue to be, a natural feature of Montana's climate [high agreement, robust evidence]; rising temperatures will likely exacerbate drought when and where it occurs. *[high agreement, medium evidence]*

- Changes in snowpack and runoff timing will likely increase the frequency and duration of drought during late summer and early fall. *[high agreement, medium evidence]*

- A warming climate will strongly influence Montana's snowpack, streamflow dynamics, and groundwater resources, with far-reaching consequences for social and ecological systems. *[high agreement, medium evidence]*

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[11] A reminder that throughout the MCA we assess our confidence in the key messages by considering a) the level of agreement among experts with relevant knowledge, and b) the quality of the evidence. We use these two factors and the criteria described in the National Climate Assessment to assign the confidence ratings expressed in this chapter. See sidebar titled "Expressed Confidence in MCA Key Messages" in the Introduction chapter.

INTRODUCTION

Our discussion focuses on climate as a principal driver of change for water resources. However, it is important to note that there are many additional drivers beyond climate, such as population growth and associated changes in land use, that strongly influence our demand for water both now and into the future. Indeed, much of Montana's water is already fully allocated to various uses (Table 3-1) (Arnell 1999; VörÖsmarty et al. 2000; Montana Department of Natural Resources and Conservation [MT DNRC] 2015), suggesting that creative and collaborative water management strategies will be essential for sustaining abundant and clean water into the future (see Missouri River sidebar).

Table 3-1. Water use in Montana from the Montana State Water Plan (MT DNRC 2015). Water use can be non-consumptive (e.g., hydropower where water returns to the surface water system), partially consumptive (e.g., irrigation where some water returns to the system), or consumptive (e.g., reservoir evaporation where water is non-recoverable with respect to continued surface water use). See the DNRC Regional Basin Plans (MT DNRC 2014a, b, c, d) for additional local detail. Also note that water used for hydropower is often counted multiple times as it travels through a series of power-generating plants.

Water usage	Annual acre-feet (m^3)	% of category
Total Water Use		
Hydropower	72,000,000 (8.9x1010)	85.9
Irrigation diversion	10,395,000 (1.3x1010)	12.4
Reservoir evaporation	1,002,000 (1.2x109)	1.2
Municipal, stock, industrial, and domestic use	384,000 (4.7x108)	0.5
Consumptive Water Uses		
Agricultural irrigation	2,414,000 (3.0x109)	67.3
Reservoir evaporation	1,002,000 (1.2x109)	28.0
Municipal	72,000 (8.9x107)	2.0
Stock water	42,500 (5.2x107)	1.2
Thermoelectric	27,400 (3.4x107)	0.08
Domestic	13,900 (1.7x107)	0.4
Industrial	10,400 (1.3x107)	0.03

Basin Study of the Missouri River Watershed

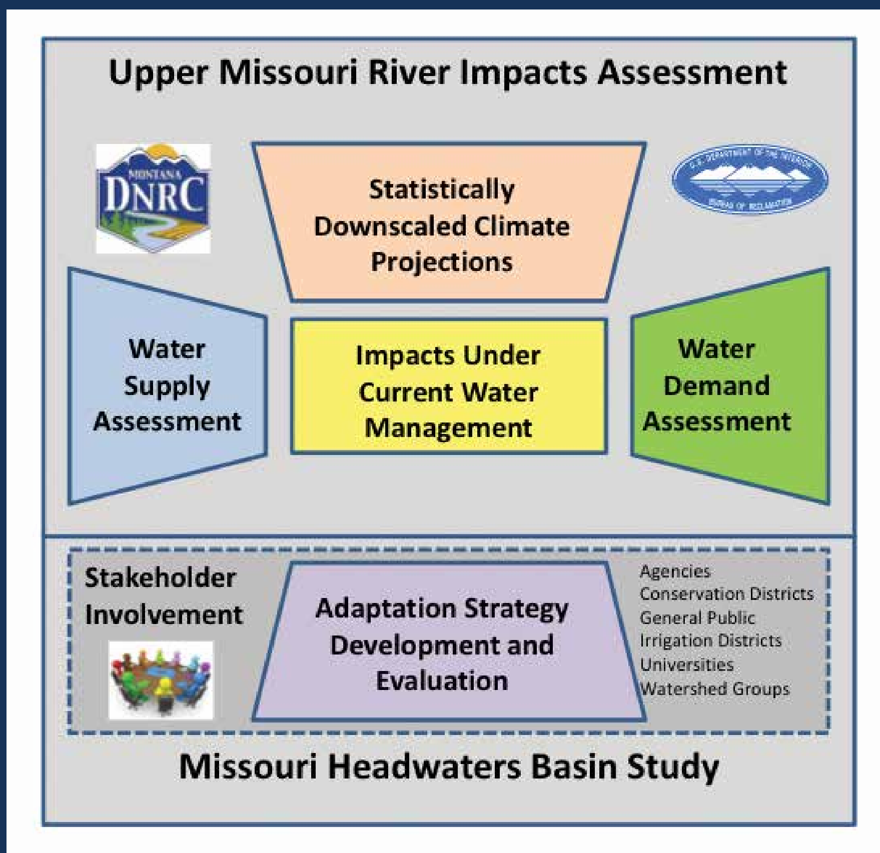
The current Montana Climate Assessment is focused on understanding relationships between climate change and water resources, with minimal focus on how water use and water management interact with climate. To help advance this important knowledge gap, the Montana Department of Natural Resources and Conservation is partnering with the US Bureau of Reclamation (Reclamation) to conduct a Basin Study of the Missouri River watershed from the headwaters to Fort Peck Reservoir, including the Musselshell River basin (USBR 2014b).

Purpose.—The purpose of the Basin Study is to understand potential future changes in basin water supplies and demands, and to analyze possible adaptation strategies for providing water needs into the future. The study builds on Reclamation's Upper Missouri Impact Assessment (USBR forthcoming) and the Montana State Water Plan (MT DNRC 2015), which evaluate how existing infrastructure would perform under anticipated future conditions.

Modeling.—As part of the study, climate and hydrology models will be used to project future water supplies and demands for the Missouri River and its major tributaries. The output from these models will serve as input data to a river-system management model that simulates streamflows, water diversions, water use, return flows, and reservoir operations. Reservoirs simulated in the model include Clark Canyon, Canyon Ferry, Gibson, and Tiber reservoirs, as well as some smaller state and private projects.

Desired results.—Output from the river system model is being used to identify likely imbalances in water supply and demand as compared to past and existing operations under known climate and hydrologic conditions.

Model output will be used to evaluate adaptation and mitigation strategies including reservoir operational changes, modification of existing facilities, and improved water management. Public participation is a key element of the Basin Study, especially for identifying and developing adaptation strategies.



Text and figure contributed by Larry Dolan (MT DNRC) and Marketa McGuire (US Bureau of Reclamation).

Climate change and the water cycle

The effects of climate change on Montana's water resources can be best understood by starting with a brief description of the water cycle (Figure 3-1). The water cycle refers to the continuous movement of water from the atmosphere to the Earth's surface and back, shifting between gaseous (water vapor), liquid, and solid (snow or ice) phases. Each of these phases of the water cycle can be impacted by climate change.

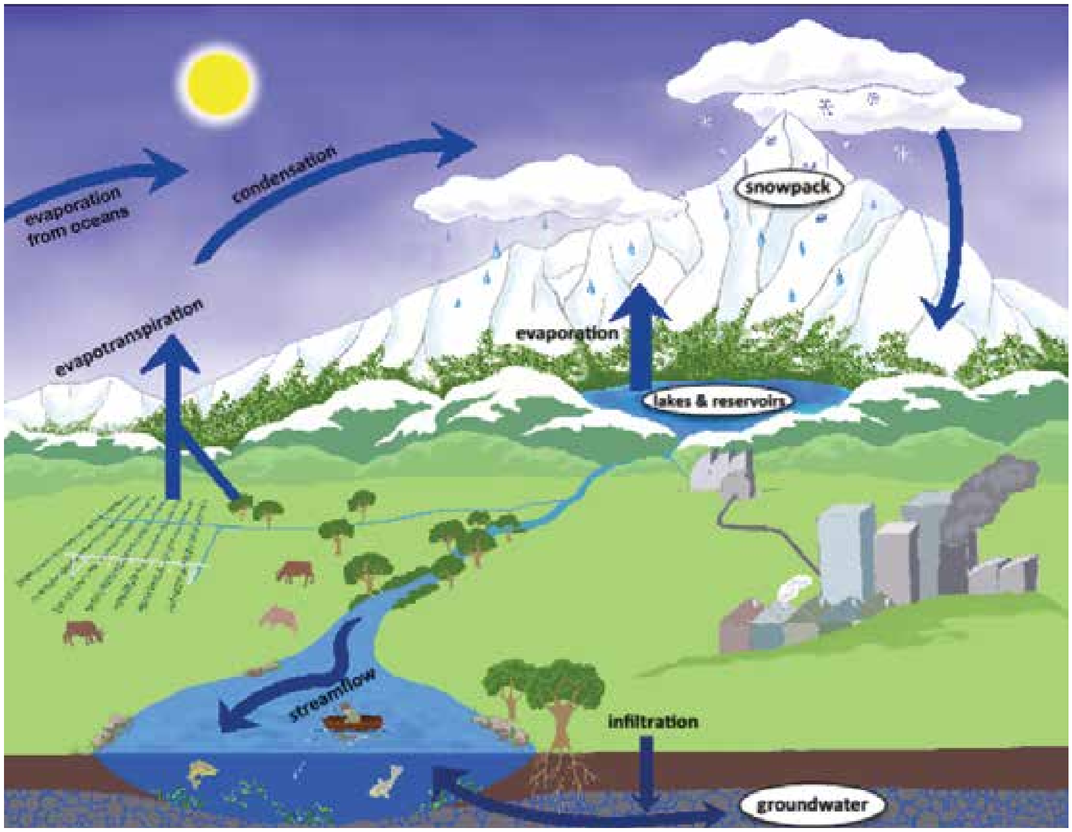


Figure 3-1. Simplified schematic of the water cycle. Artwork by Jenny McCarty.

The primary atmospheric source for the water cycle is evaporated water from the ocean. In Montana, much of the winter snowfall that accumulates in the mountains melts in the spring to produce streamflow and recharge groundwater aquifers. This same water supports municipalities and industry throughout the year and is used to irrigate crops in the summer. Some irrigation water will directly support plant growth and some will trickle back into groundwater aquifers. Much of this same water will return to the atmosphere as water vapor through evaporation or plant transpiration, thus completing the water cycle. Precipitation as rainfall is a significant part of the water cycle in Montana, and its contribution to runoff can exceed that of snowfall in prairie environments in the state.

Changes in temperature near the Earth's surface will have large effects on how water enters Montana (e.g., as rain or snow), how it is distributed among the major storage pools, and how it moves or changes from one component of the water cycle to another. For instance, elevated temperatures can accelerate the loss of snowpack and lead to greater rates of evapotranspiration and the movement of water from the Earth's surface back to the atmosphere. Additionally, increases in greenhouse gas concentrations and associated warming can affect how efficiently plants use or store water, further influencing important components of the water cycle.

Montana water resources

The vast majority of water that enters Montana comes as rain or snow at higher elevations (Figure 3-2) (MT DNRC 2014a, b, c, d; MT DNRC 2015). Although some of Montana's water originates in Wyoming or adjacent Canadian provinces, over 80% is derived from within state boundaries, hence Montana's designation as a "headwaters state."

In a typical year, the majority of western Montana's precipitation falls as winter snow. This natural bank of water supports Montana's ecosystems and economies as it melts in the higher elevations and then flows east or west off the Continental Divide. In contrast, much of central and eastern Montana receives the majority of its annual precipitation as spring and summer rains. Thus, a solid understanding of how climate influences a) snowpack in the western portion of the state, and b) rainfall timing and amount in the remainder of the state is essential for making projections about the future of our state's water supply.

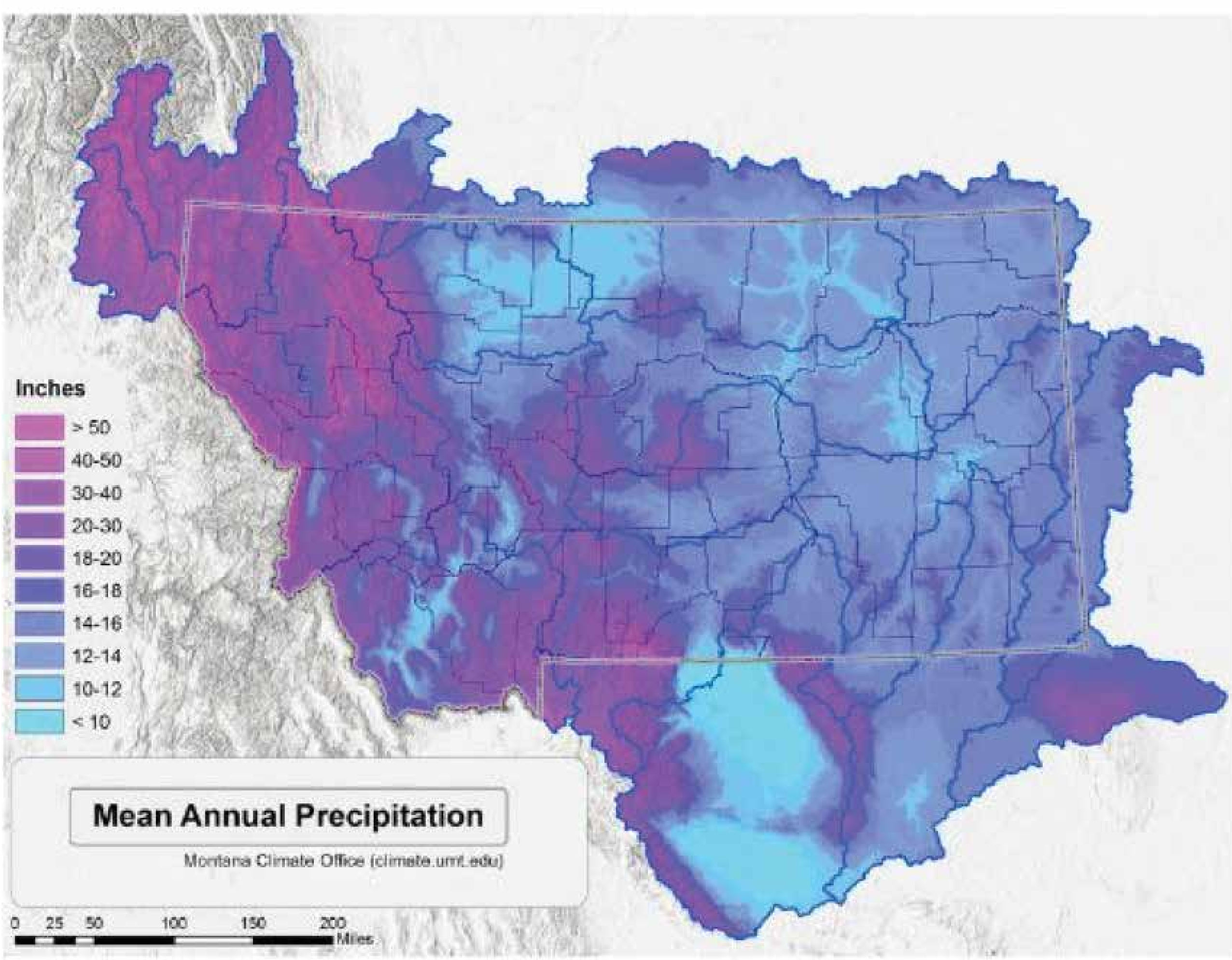


Figure 3-2. Mean annual precipitation for the years 1981-2010 from Daymet. Daymet is produced by the Oak Ridge National Laboratories from methods originally developed at the University of Montana. The data are derived from elevation and daily observations of precipitation in inches from ground-based meteorological stations. Figure courtesy Montana Climate Office.

The major rivers of Montana export more than 40 million acre-feet of water/yr (4.9x1010 m^3/yr)[12]—more than twice the capacity of Flathead Lake—with the majority, approximately 60%, generated in the Clark Fork and Kootenai river basins west of the Continental Divide (Figure 3-3). (MT DNRC 2014a). These western watersheds are considerably smaller than those east of the Continental Divide, but tend to be much wetter because they are more influenced by Pacific Northwest climate patterns. East of the Continental Divide, continental air masses dominate and the climate is generally more arid. Most of the water that leaves the state east of the Continental Divide (approximately 16 million acre-feet/yr [2.0x1010 m^3/yr]) is generated in the Yellowstone and Missouri river watersheds.

Statewide Average Annual Flow Accumulation

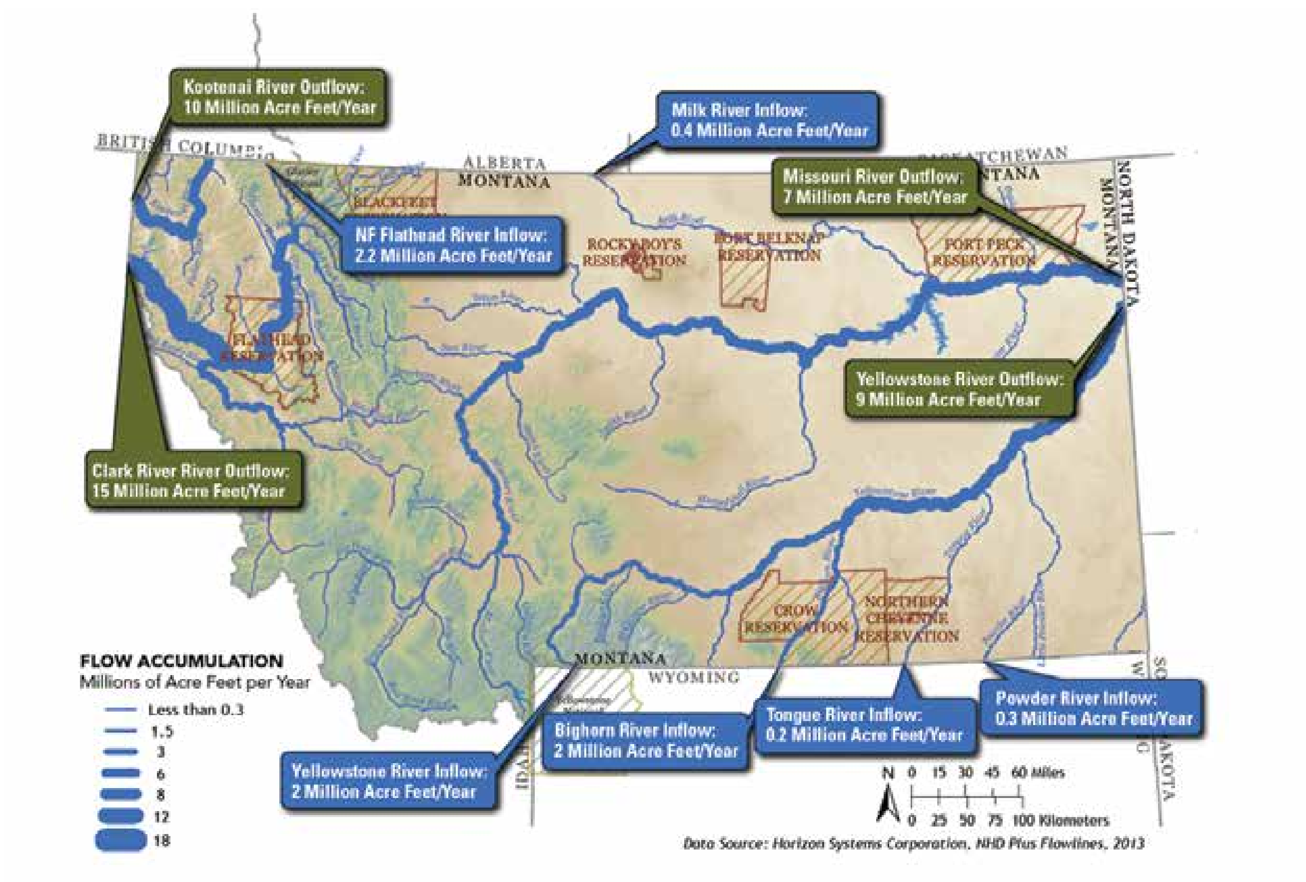
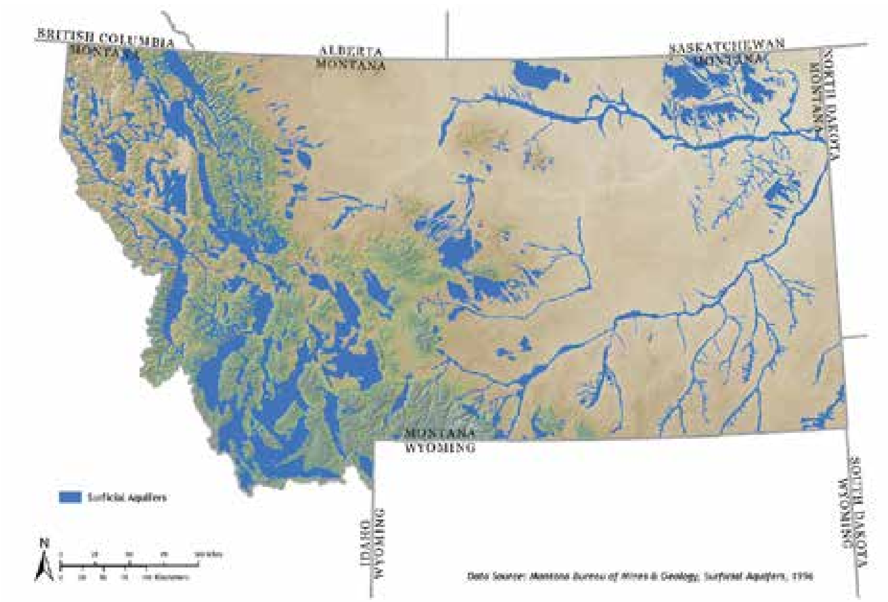


Figure 3-3. Statewide average annual flow accumulation as inflows and outflows in millions of acre-feet/yr (1 acre-foot = 1233 m^3). Image from the Montana State Water Plan 2015, courtesy of the Montana Department of Natural Resources and Conservation (MT DNRC 2015).

[12] 1 acre-foot is 325,851 gal (1233 m^3), enough water to cover an acre of land 1 ft (0.3 m) deep.

Groundwater is another large and important resource and component of the water cycle in Montana (Figure 3-1). Most of the groundwater used in the state comes from shallow sand or gravel aquifers in river floodplains (Figure 3-4). These sources tend to fluctuate rapidly (days to months) in response to precipitation and evaporation or changes in surface water flow. Other deeper sources of groundwater exist in bedrock aquifers, either where steep mountain fronts meet river valleys (especially in western Montana), or within large subsurface limestone and sandstone rock formations (especially in central and eastern Montana; Figure 3-4).

Montana Surficial Aquifers



Montana Bedrock Aquifers

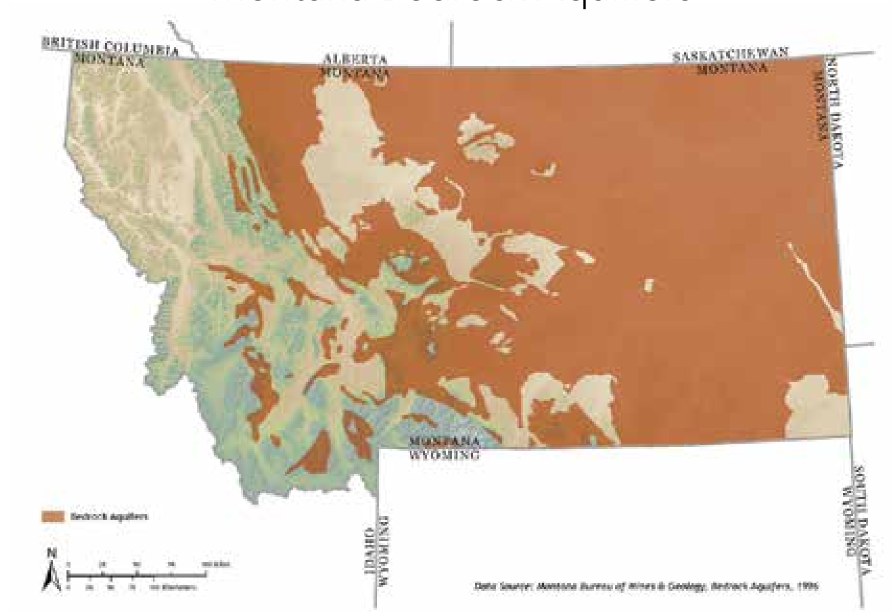


Figure 3-4. Distribution of surface-level (i.e., surficial) and bedrock aquifers across Montana. Images from MT DNRC, Montana State Water Plan 2015 (MT DNRC 2015).

Groundwater resources are critical for water users, but also contribute significantly to natural streamflow throughout the year. Thus, understanding relationships between climate and different types of groundwater resources is important for maintaining Montana's water security. The Montana Bureau of Mines and Geology tracks long-term groundwater-level change in the state's principal aquifers (see groundwater section).

Geographic and temporal setting

Montana is the fourth largest state (by land area) in the US and contains substantial topographic variation. As a result, and as previously described (see Climate chapter), climate conditions vary significantly across the state. To best represent the influence of climate variations on water resources, this chapter focuses on eight rivers and their watersheds (Figure 3-5; note that some watersheds—for example, Poplar River and others—extend beyond the state boundaries). These focal rivers and watersheds, chosen across the state's seven National Oceanic and Atmospheric (NOAA) climate divisions (Figure 2-3),[13] include:

- Climate division 1—Clark Fork River at Saint Regis
  —Middle Fork of the Flathead River at West Glacier
- Climate division 2—Missouri River at Toston
- Climate division 3—Marias River near Shelby
- Climate division 4—Musselshell River at Mosby[14]
- Climate division 5—Yellowstone River at Billings
- Climate division 6—Poplar River near Poplar
- Climate division 7—Powder River near Locate

For many of these river basins, both snowpack and streamflow have been recorded by the US Geological Survey (USGS) and the Natural Resources Conservation Service (NRCS) since the 1930s or 1940s. In one instance, the Marias River, streamflow information dates back to the 1910s. These data provide an extensive resource for understanding the historical range of snowpack and streamflow across the state.

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[13] For more detail on our focal rivers and watersheds, see Appendix 3-1 on the MCA website.

[14] The characterization of climate division 4 focuses on the plains basins within the division.

Selected Focal Watersheds

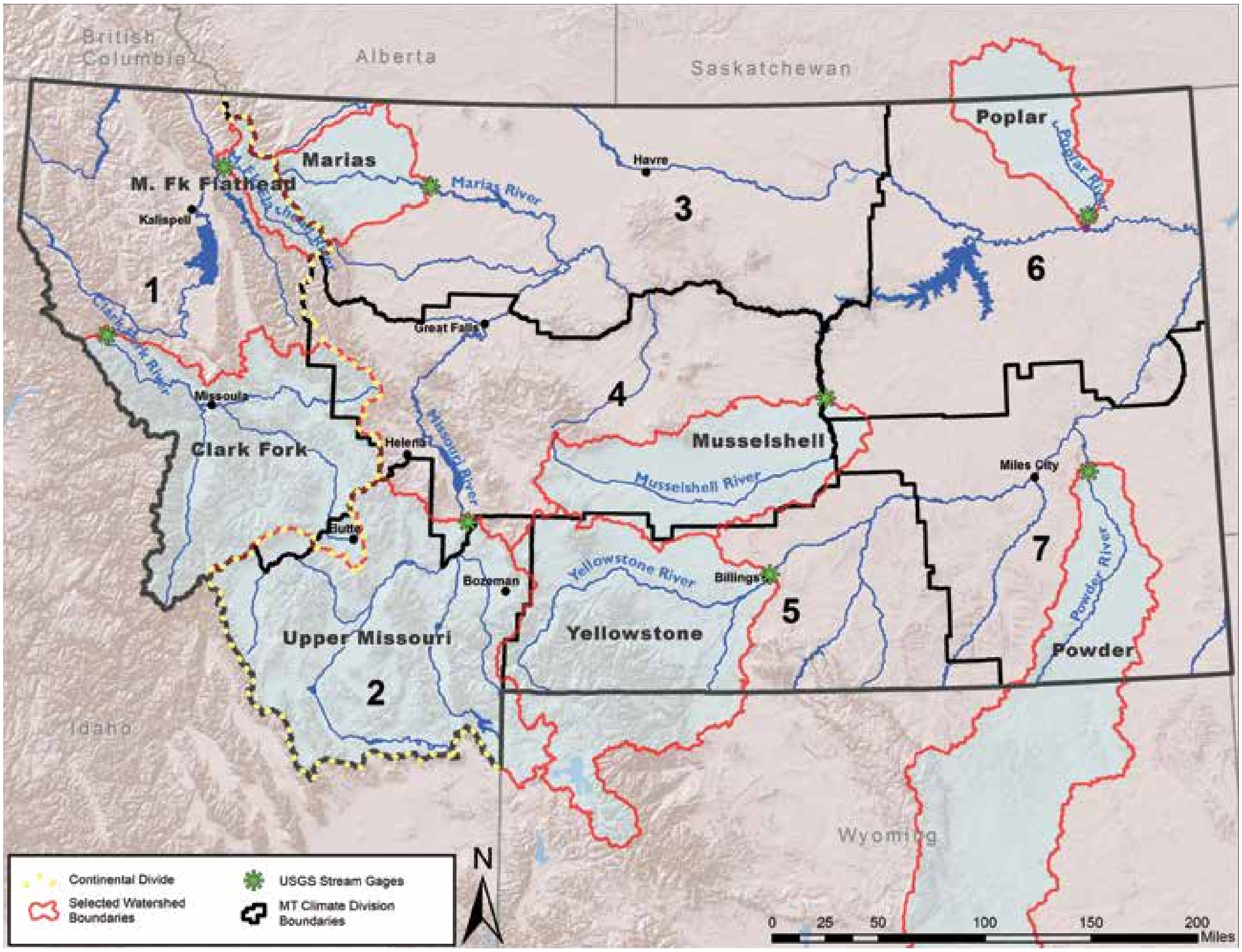


Figure 3-5. The focal rivers for this assessment, including black outlines of the seven climate divisions (see Water chapter), contributing watersheds (red), river gage locations (green), and the Continental Divide (dotted).

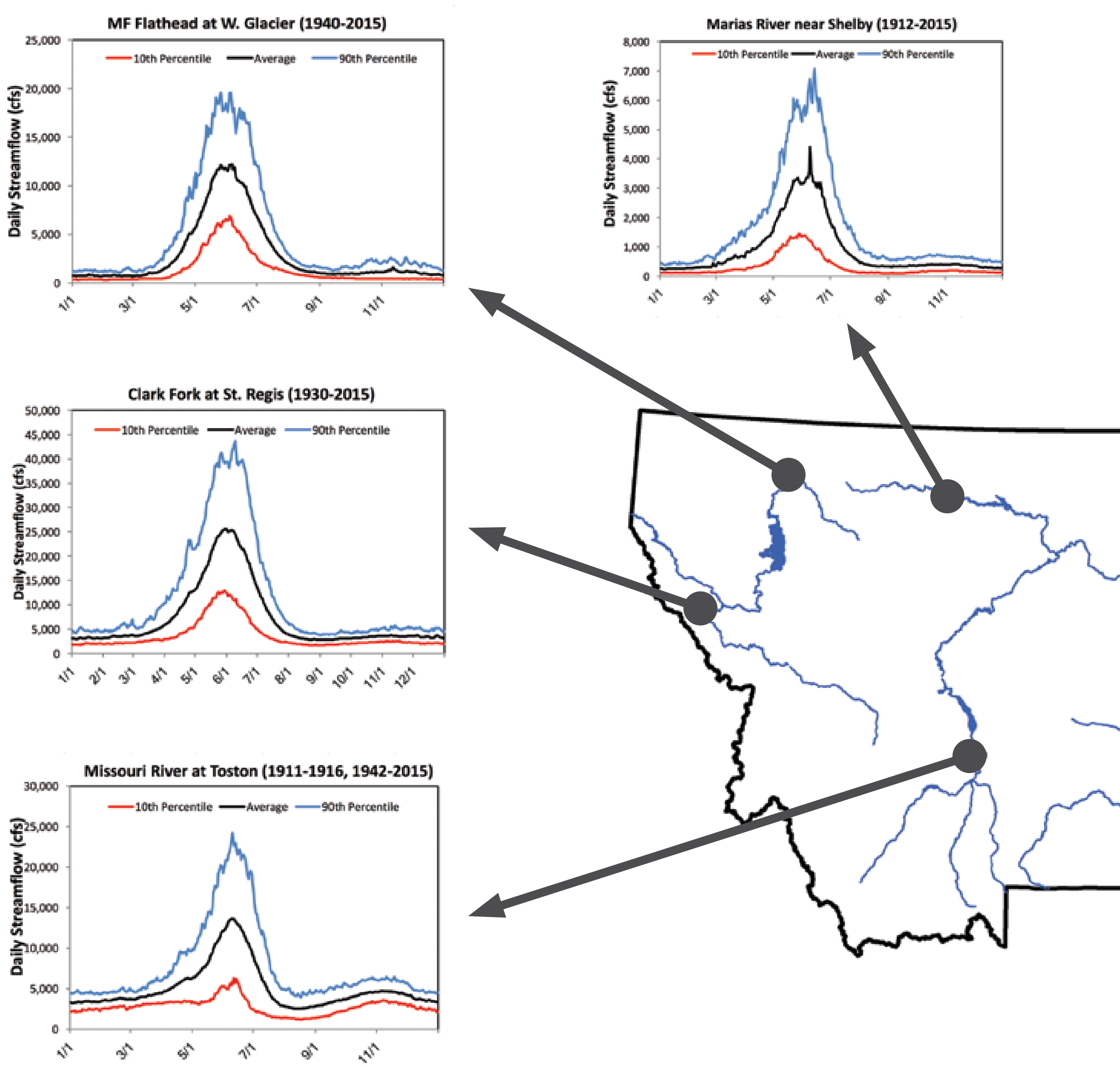
Our focal rivers were selected to represent differences in streamflow regimes across Montana's climate divisions. Individual USGS stream gaging stations were selected based on two principal criteria:

1 at least 70 yr of streamflow data (preferably continuous), and

2 low to moderate upstream water use or levels of water development representative of the region (note that the vast majority of rivers in Montana are influenced to some degree by water use, and these data do reflect some human modification).

Patterns of streamflow for large rivers in Montana reflect a general dependence on snowpack and snowmelt, with peak flows typically occurring in the spring and low flows occurring in late summer and persisting through the fall and winter. However, the magnitude and timing of runoff vary among rivers across Montana, resulting largely from variation in watershed elevation and the seasonal

Annual Hydrographs and Long-term Flow Percentiles for Focal Rivers



distribution of precipitation as snow or rain. Changes in river levels are measured by hydrographs. Within our representative sample of Montana rivers, three predominant hydrograph patterns are evident (Figure 3-6): snowmelt-dominated, dual-peaked, and low-elevation plains.

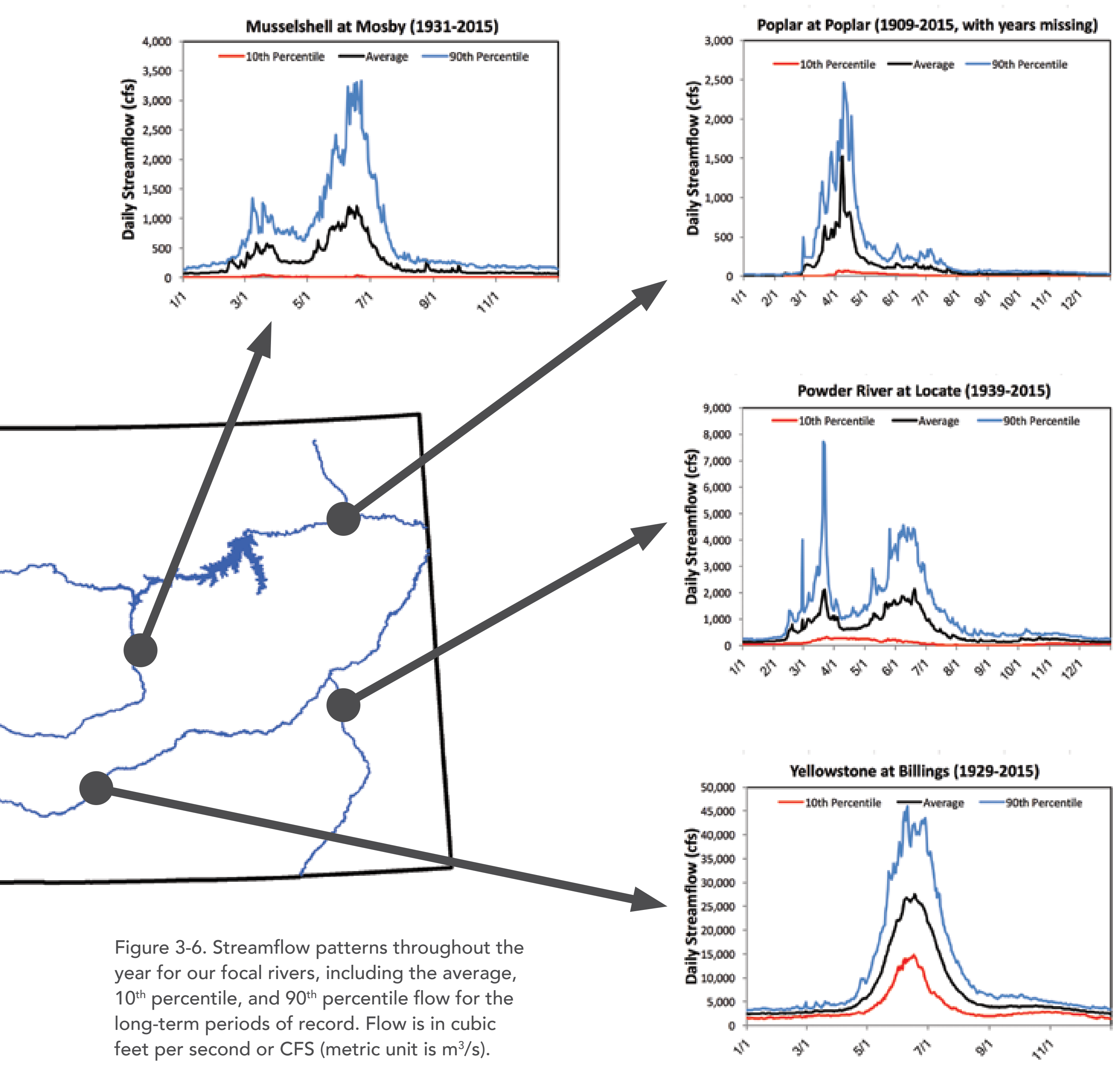


Figure 3-6. Streamflow patterns throughout the year for our focal rivers, including the average, 10th percentile, and 90th percentile flow for the long-term periods of record. Flow is in cubic feet per second or CFS (metric unit is m^3/s).

Snowmelt-dominated hydrograph.—The vast majority of rivers in western and central Montana are classified as snowmelt dominated. Representative snowmelt-dominated rivers in Montana include the Middle Fork of the Flathead River at West Glacier, the Clark Fork River at Saint Regis, the Yellowstone River at Billings, the Missouri River at Toston, and the Marias River near Shelby.

Winter and spring precipitation, coupled with seasonal patterns of solar radiation, heavily influence streamflow in these rivers. Warming temperatures in March and April initiate the snowmelt process, driving a significant rise in the hydrograph (Figure 3-6). Spring precipitation (as rain) and additional rapid snowmelt, with a large peak in flows during May or June, further augment streamflow. Snowmelt recession then gives way to low base flow that dominates for the remainder of the year (typically late fall to early spring).

Variations within this category occur. Spring runoff in snowmelt-dominated rivers west of the Continental Divide often starts and peaks a few weeks earlier than those to the east. The earlier runoff results because of generally warmer temperatures and lower elevations (e.g., compare the warmer and lower-elevation Clark Fork River at Saint Regis to the Yellowstone River at Billings). In contrast, snowmelt and peak flow tend to lag for snowmelt-dominated rivers at high elevations and with north-facing slopes due to cooler temperatures.

Several snowmelt-dominated rivers in Montana, particularly in agriculturally dominated basins, exhibit a small increase in streamflow during September and October. This pattern can be attributed to the end of the irrigation season, fall precipitation, residual groundwater return flows from irrigated areas, and a general reduction in plant evapotranspiration. The Missouri River at Toston, for example, demonstrates such a pattern (Figure 3-6).

Dual-peaked hydrograph.—Some Montana rivers are fed by a combination of high- and low-elevation snowpack, creating an annual hydrograph with two distinct peaks. These rivers are generally located in the central and eastern parts of the state, for example the Musselshell River at Mosby and the Powder River near Locate (Figure 3-6). The earlier streamflow peak, centered in March-April, results from early snowmelt as low-elevation prairies thaw. The second hydrologic peak, generally occurring in June, results from snowmelt and precipitation at higher elevations. As in the snowmelt-dominated hydrographs, streamflow then declines throughout the summer, reaching base flows in August or September.

Low-elevation plains hydrograph.—Low-elevation watersheds, also largely located in central and eastern Montana, show more erratic spring flows, as well as far greater interannual variation due to the predominant influence of rain instead of snowmelt. Streamflow in these rivers typically begins to rise in February or March, peaks in April, and recedes by the end of May, with small increases in summer streamflow due to localized rain events. This type of runoff pattern is only evident among plains watersheds without mid- or high-elevation headwaters, such as the Poplar River watershed at Poplar (Figure 3-6). Hydrographs of larger rivers in the eastern part of the state, such as the lower Yellowstone and Missouri rivers, are influenced more strongly by high-elevation snowmelt in the headwaters, and therefore do not follow the low-elevation plains pattern.

We can expect that climate change will have varying effects on these different categories of streams, which we address below.

Future projections

Climate models (see Climate chapter) provide a method for projecting future climate scenarios in Montana. By linking climate models to water cycle models, we can also generate projections about how climate change is likely to influence Montana's water resources.

This chapter presents climate model-based hydrologic projections of snowpack and streamflow for our eight focal river basins. These projections derive from a national modeling effort undertaken by a large collaborative team of agencies, universities, and research centers (LLNL undated). The models employed herein were also used by the Intergovernmental Panel on Climate Change (Stocker et al. 2013) and the National Climate Assessment (Melillo et al. 2014).

Hydrologic projections reported in this chapter comprise 31 complementary general circulation models that were downscaled using the Bias-Correction Spatial Disaggregation technique and incorporated into the Variable Infiltration Capacity hydrologic model (USBR 2014a). All of the models employed include some level of uncertainty that informs how much we should trust the results. For example, hydrologic models are linked to the water cycle and climate-related changes in certain elements of the water cycle, such as evapotranspiration, can be particularly difficult to quantify. The hydrologic projections in this assessment are compared to a baseline period of 1970-2000. These baseline streamflows are also generated by the model and may differ from actual historical flow data. Our analysis focuses on relative changes in flow, rather than absolute streamflow values. Any future assessments aiming to offer precise estimates of projected streamflow volumes will need to undergo a model calibration process (USBR 2016).

Throughout the chapter we use the following convention to represent model agreement for the hydrologic projections:

- Very high confidence.—If all the models agree on the direction (positive or negative) of a particular outcome (e.g., reduced April 1 snowpack).
- High confidence.—80% of the models agree.
- Low confidence.—60% of the models agree.
- No confidence.—If 50% of the models show one result (e.g., a future increase in snowpack) and 50% show the other (e.g., a future decrease in snowpack), we have virtually no confidence in the future projection.

Chapter organization

In the remainder of this chapter, we discuss how climate change will affect key parts of the water cycle. The focal areas discussed in the remainder of this chapter are:

- Snowpack.—We examine how changes in climate have influenced snowpack in Montana and the region; and we present model projections for snowpack in the future.
- Snowmelt and Runoff Timing.—We show historical trends in snowmelt and runoff timing; examine climate factors that most influence these patterns; and present model projections for stream runoff in the future.
- Annual Streamflow.—We examine historical trends in total annual streamflow; discuss what climate factors most influence these patterns; and present model projections for the future.
- Groundwater Resources.—We discuss how climate change and groundwater resources interact across the state.
- Drought.—We present factors that influence long-term persistent drought, as well as seasonal low flows in summer months; and we explore how drought risk might change in the future.

Montana's Disappearing Glaciers

Glaciers are slowly moving masses of ice formed by the accumulation and compaction of snow. The loss of Montana glaciers—a visible local example of climate warming—is an important bellwether of a broader set of changes to Montana's water cycle. Changes to the water cycle are expected to have far-reaching effects on human and natural systems (IPCC 2014).

Increasing temperatures.—Elevated greenhouse gas concentrations have led to an increase in average temperatures throughout Montana (see Climate chapter). It is likely that this trend will continue into the future.

Decreasing glaciers.—One of the most visible manifestations of climate warming in Montana is the rapid melting of the last remaining glaciers in Glacier National Park. A repeat photography project conducted by the USGS highlighted the dramatic changes over the past 150 yr (photos).

When geologists first surveyed Glacier National Park in the 1850s, approximately 150 glaciers existed; at present, only 25 of these glaciers or ice fields remain (Chaney 2016). Most concerning is the fact that these changes have occurred over a relatively short period, with the majority of glacial melt occurring since the 1980s (Pederson et al. 2011b). Scientists predict that the vast majority of glacial ice in Glacier National Park will disappear within the next 20 yr (USGS 2016).

What is driving the loss of permanent ice from Glacier National Park? Researchers have attributed glacial decline to increasing temperatures, which have reduced the period of glacial accumulation and extended the period of summer ice melting (ablation). The result is a net loss of ice over time (Hall and Fagre 2003; Pederson et al. 2004). Other studies have similarly described the decline of glaciers and snowfields in the Northern Rockies and Pacific Northwest (e.g., Mote et al. 2005; Moore et al. 2009; Nolin et al. 2010), suggesting that this pattern is much larger in scale than Glacier National Park.

Repeat photographs of Boulder Glacier in Glacier National Park. The photos are from 1932 (left) and 2005 (right). Courtesy of USGS Northern Rocky Mountain Science Center.

SNOWPACK

Key Message

Montana's snowpack has declined over the observational record (i.e., since the 1930s) in mountains west and east of the Continental Divide; this decline has been most pronounced since the 1980s. Warming temperatures over the next century, especially during spring, are likely to reduce snowpack at mid and low elevations. [high agreement, robust evidence]

The influence of climate on snowpack is one of the major linkages between climate change and water supply. Snowpack in the mountains of Montana stores and provides water to downstream users and ecosystems in both the US and Canada. Water generated by Montana's snowpack travels to the Pacific, Atlantic, and Arctic oceans. Indeed, western Montana is often called the Crown of the Continent because headwater streams originating there give rise to the major rivers that drain three of North America's largest watersheds, those of the Columbia, Missouri-Mississippi, and Saskatchewan rivers.

Precipitation that falls at higher elevations during the cold winter months accumulates as snow until spring when temperatures increase and snowmelt begins. In Montana's mountainous areas, winter snowfall represents the majority (62-65%) of total annual precipitation (Serreze et al. 1999), while in the eastern plains, the contribution of snowfall to total precipitation is considerably less (WRCC undated). All of Montana's major rivers that contain headwaters above 7000 ft (2100 m) elevation are considered snowmelt-dominated systems in which precipitation as snow is a primary driver of year-to-year variability in streamflow. This snowpack acts as a natural reservoir, slowly releasing water during the spring and early summer, sustaining approximately 2 million acres (0.8 million ha) of irrigated farmland in Montana (Pierce et al. 2008; Vano et al. 2010; USDA-NASS 2015). A sufficient supply of water (especially during the summer) is not only important for maintaining Montana's agricultural industry, but it also underpins our natural ecosystems and the state's rapidly growing tourism economy (Power and Power 2015, 2016).

Most of Montana's annual snowfall arrives from mid October through mid May (although snowfall has been observed in all 12 months in the mountains of Montana). Snowfall is strongly influenced by local and regional climate. Average annual snowfall varies considerably throughout the state, from roughly 20 inches (0.5 m) in the plains of northeastern Montana, to over 400 inches (10.1 m) in several mountain locations in the west (WRCC undated). (Note that annual snowfall totals are higher than annual precipitation totals—as in Figure 3.2—because of the different physical properties of frozen versus liquid water).

Measuring snowpack

Reliable snowpack measurements are essential for estimating water supply and assessing the risk of drought or floods (MT DNRC undated). The US Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS undated) measures Montana's snowpack through two networks:

- Over 90 automated SNOwpack TELemetry (SNOTEL) sites.—First established in Montana during the early-1970s, SNOTEL sites gather high-resolution data year-round, and remotely transmit snowpack and climate information every hour.

- Roughly 100 Snow Course survey locations.—First established in Montana in the 1920s-1960s, Snow Course data consist of hand-collected snowpack measurements. These measurements, typically gathered near the first of each winter month, provide our longest direct records of regional snowpack.

Scientists usually report snowpack as snow water equivalent (SWE). SWE represents the amount of liquid water contained within a column of snow or, more precisely, the height of water that would remain in a standardized area if the snowpack melted. When examining multi-year trends in snowpack, scientists and managers often use the April 1 SWE measurement to represent peak snowpack and total accumulated cold-season precipitation. Although April 1 SWE values can underestimate actual peak snowpack in the Northern Rockies (Bohr and Aguado 2011), this metric functions as a reasonable approximation for maximum snowpack at the watershed scale (Serreze et al. 1999; Pederson et al. 2011b) and as an indicator of potential spring streamflow in Montana.

April 1 is considered an optimal date for examining trends because it is the most continuously collected date in the observational record; some sites have been recorded continuously for over 80 yr (Mote et al. 2005).

Montana's diverse geography and topography influence patterns of snowpack accumulation and snowmelt

Geography.—In Montana, the Continental Divide exerts a marked influence on climate patterns and resulting snowpack:

- Areas west of the Continental Divide typically exhibit milder winters, cooler summers, and a longer growing season due to the influence of warm Pacific air masses (see Climate chapter). Figure 3-2 shows that average annual precipitation is highest west of the Continental Divide (MT DNRC 2015). As a result, total water yields and water yield relative to watershed area are greatest in climate division 1 (Figure 3-5) (MT DNRC 2015).

- Areas east of the Continental Divide experience more extreme seasonal temperature fluctuations and a shorter growing season due to greater influence by drier continental air masses (see Climate chapter) (WRCC undated).

Topography.—Mountains west of the Continental Divide are generally situated at lower elevations than those east of the Continental Divide, yet the western mountains still receive more snowfall on average each year (Figure 3-2). SNOTEL stations record the highest snowfall totals west of the Continental Divide in the Kootenai, Flathead, and Clark Fork basins. Several of these stations are located at relatively low elevations (5000-6500 ft [1500-1980 m]), but receive over 40 inches (1 m) of SWE each year. By comparison, the highest annual snowpack totals east of the Continental Divide (20-35 inches [0.5-0.9 m] of SWE) are generally located at elevations over 8000 ft (2400 m) (NRCS 2016).

For most mountainous areas in Montana, SWE typically peaks in April or early May, but this can vary depending on elevation, aspect (e.g., north versus south facing), and relative position west or east of the Continental Divide. Low-elevation SNOTEL sites west of the Continental Divide in the Kootenai Basin (approximately 4200 ft [1280 m]) typically record maximum snowpack at the end of March and snow is absent by early May. In contrast, high-elevation sites (over approximately 8500 ft [2590 m]) in the headwaters of the Yellowstone and Missouri basins exhibit peak SWE values in mid May, and some north-facing slopes can retain snow through the end of June (NRCS 2016).

Snowpack accumulated at high elevations tends to be more stable and persist longer than at low elevations, largely as a result of colder temperatures at high elevations. Snowpack at higher elevations is also less prone to melt during short warm spells in the early spring that can degrade snowpack at lower elevations.

Long-term variation in snowpack and the importance of ocean-atmosphere linkages

As discussed in the Climate chapter, large-scale atmospheric patterns associated with changes in sea-surface temperatures are largely responsible for variation in Montana's weather and climate (Cayan et al. 1998; Abatzoglou 2011; Pederson et al. 2011a; Pederson et al. 2013a). Phase shifts in the Pacific Decadal Oscillation can be readily detected in the long-term records of annual snowfall. On shorter time scales, and layered on top of Pacific Decadal Oscillation variation, the Pacific North American pattern and the El Niño-Southern Oscillation cycles (see Climate chapter) can also affect variation in snowpack. During El Niño episodes, Montana tends to experience warmer-than-average temperatures and below-average precipitation, especially during the winter and spring. These anomalies decrease snowpack and result in early snowmelt (Climate Prediction Center 2016). In contrast, La Niña episodes typically result in below-average temperatures, above-average precipitation, and above-average snowpack. Exceptions to these patterns certainly exist.

Observed regional trends in snowpack

Regional trends in April 1 SWE demonstrate that average annual snowpack has declined in large portions of the American West over the period of reliable measurement (1930s to present; Figure 3-7) (Mote 2003; Hamlet et al. 2005; Mote 2006; Casola et al. 2009; Mote and Sharp 2016). Some regions, such as low-elevation sites in the northern Rocky Mountains (including Montana) and the Cascades, have experienced more drastic reductions than other sites, such as high-elevation loctions in the Sierras and central Rocky Mountains.

Trends in April Snowpack in the Western US, 1955–2016

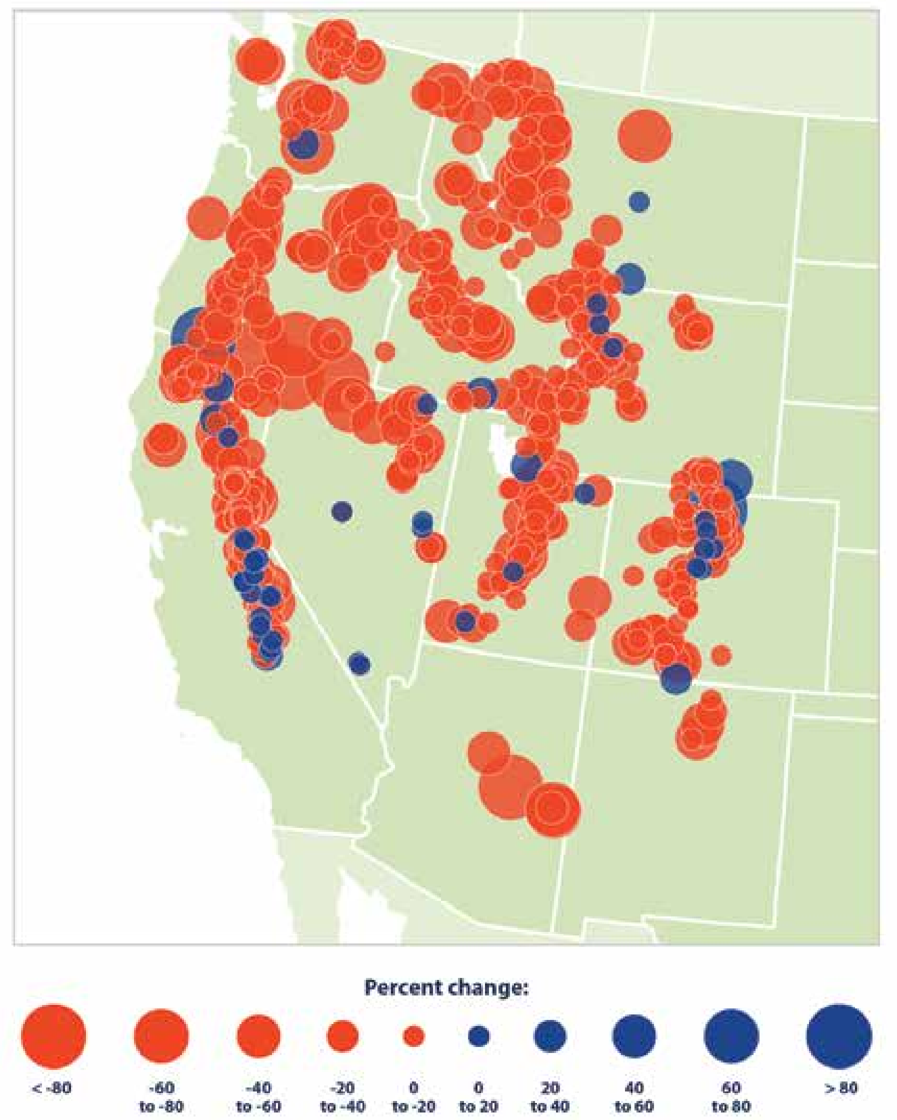


Figure 3-7. Trends in April snowpack in the western US, 1955-2016. Red bubbles indicate areas with declining snowpack; blue bubbles indicate areas with increasing snowpack. The diameter of the bubbles is proportional to the percentage change between 1955 and 2016. Figure from Mote and Sharp (2016).

However, it is important to place these recent observations in the context of much longer-term (multi-century) changes in climate. Climate reconstructions based on tree-ring measurements provide a robust tool for producing quantitative comparisons of past and present climate (Fritts 2012). One such recent reconstruction showed that declines in snowpack since the 1950s are unusually severe and synchronous across the West when viewed in the context of the past 1000 yr (Figure 3-8) (Pederson et al. 2011b). Separate studies have suggested that these recent declines in snowpack can be directly attributed to elevated greenhouse gas emissions and associated warming (Barnett et al. 2008; Pierce et al. 2008).

Long-term SWE Reconstruction for the Northern Rockies

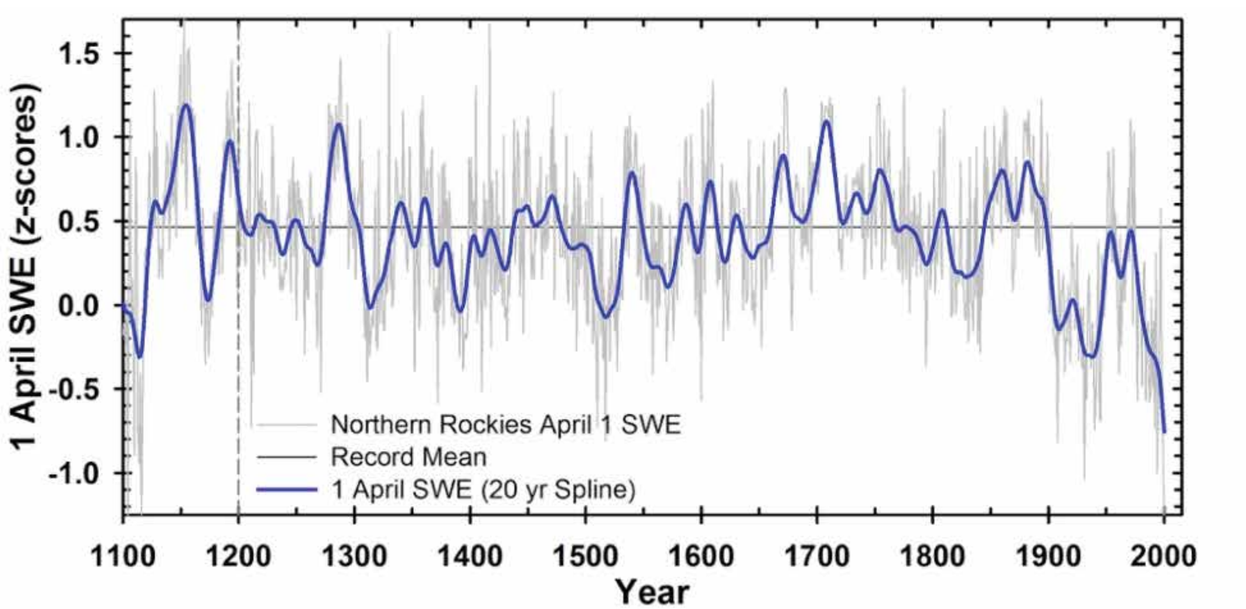


Figure 3-8. Snow water equivalent (SWE) reconstruction for the Northern Rockies based on tree-ring measurements (figure from Pederson et al. 2013a). Z-scores standardize the data to represent the number of standard deviations above or below the long-term average.

In the Rocky Mountains, spring (February-March) warming since the 1980s has been largely responsible for recent snowpack declines at mid- and low-elevation sites (Pederson et al. 2013b). Most studies agree that general declines in snowpack across the West have resulted from warming spring temperatures (Mote 2003; Hamlet et al. 2005; Mote et al. 2005; Abatzoglou 2011; Kapnick and Hall 2012; Pederson et al. 2013a; Lute et al. 2015); however, declines in winter precipitation may also be important (Clow 2010). If spring temperatures continue to warm as projected (see Climate chapter), snowpack is likely to decline even further.

Observed trends in Montana's snowpack

We conducted an updated assessment of Montana's April 1 SWE to assess variability and trends over the full record—from the late 1930s to present—of NRCS Snow Course observations.[15] We used Snow Course rather than SNOTEL data because of its longer period of record. Although studies have shown a strong correlation between Snow Course and SNOTEL April 1 SWE measurements (Serreze et al. 1999; Bohr and Aguado 2001; Dressler et al. 2006; Pederson et al. 2011a), all snowpack measurements have limitations, including the potential for human measurement error, land-use change over the period of record, poor representation for watersheds with highly complex terrain, and misrepresentation of high-elevation sites that lack measurement stations (Gillan et al. 2010; Silverman and Maneta 2016). Nonetheless, Snow Course trends are more dependable and useful for describing long-term changes to snowpack across Montana's large mountainous watersheds.

Long-term cycles in April 1 SWE are evident among all Snow Course groupings (Figure 3-9). These cycles can be attributed in part to decadal-scale climate patterns, including the Pacific Decadal Oscillation. For example, the Pacific Decadal Oscillation was in a negative phase between approximately 1960-1980, leading to above average snowpack across the state. In contrast, from the mid 1980s through approximately 2000, a positive phase led to relatively low snowpack years (Figure 3-9).

Large interannual variability in snowpack can be nested within Pacific Decadal Oscillation (and Pacific North American) driven patterns (e.g., see the high snow years of 1996 and 1997 that occurred during a 25-year period of below average snowpack).

Medicine Lake National Wildlife Refuge.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

[15] For more detail on our snowpack analysis methods see Appendix 3-2 on the MCA website.

Montana Trends in April 1 SWE from Snow Course Data

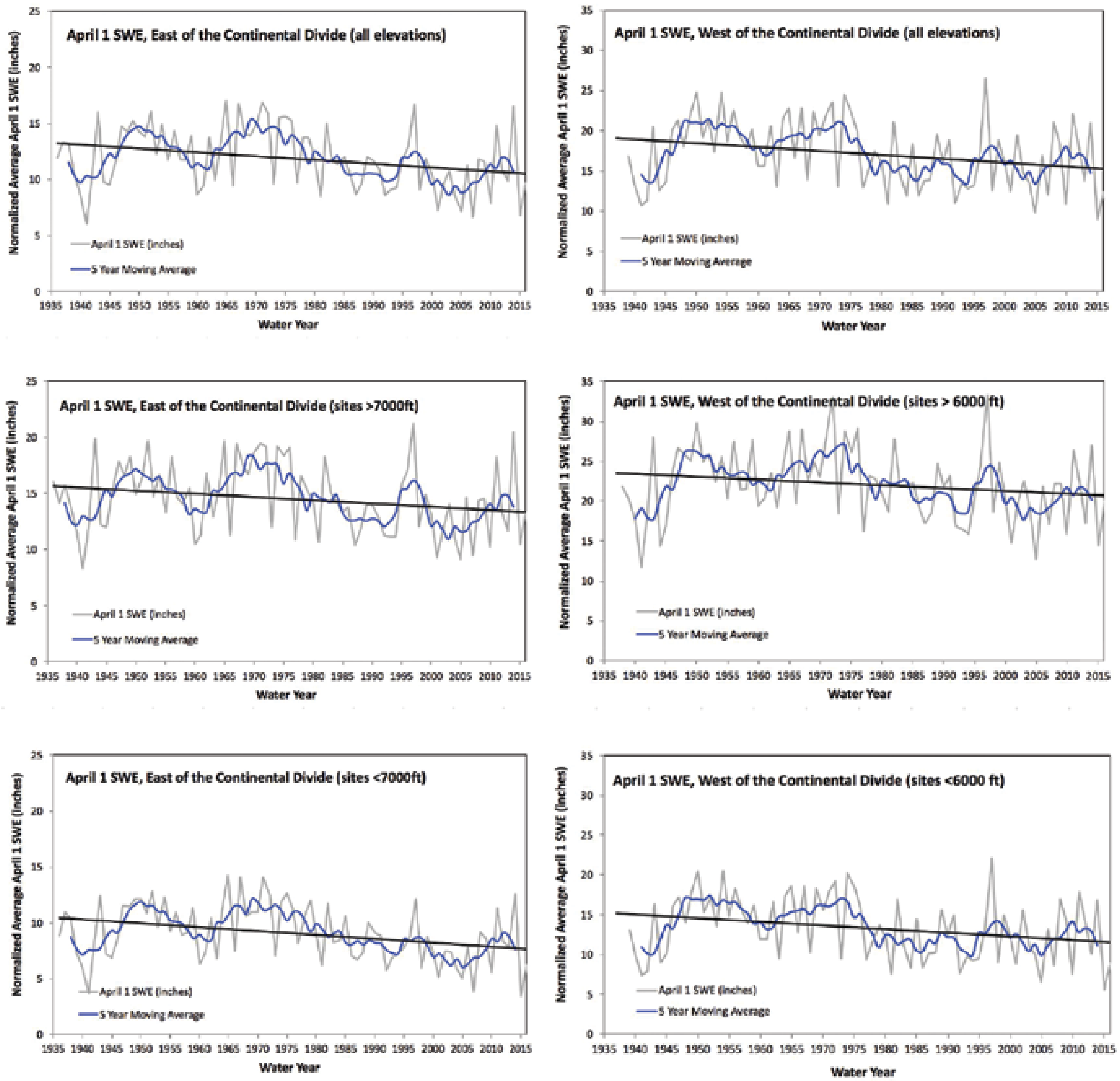


Figure 3-9. Normalized April 1 SWE based on Snow Course measurements west and east of the Continental Divide. The upper panel in each column shows data summarized from all Snow Course stations west or east of the Continental Divide. The middle and lower panels show patterns of SWE at high or lower elevations. Black lines represent simple downward trends and are not meant for statistical inference.

Snow Course groupings on both sides of the Continental Divide show long-term downward trends in April 1 SWE (Figure 3-9, Table 3-2). This observation is consistent with other studies that have described shrinking snowpack volumes in Montana and elsewhere in the western US (Mote et al. 2005; Pederson et al. 2013a; Mote and Sharp 2016). In general, April 1 SWE in Montana has declined roughly 20% over the last 80 yr, and this decline is most pronounced at lower elevation sites (Table 3-2).

Table 3-2. Linear trends in snowpack for particular elevations east and west of the Divide, calculated from data in Figure 3-9.[16]

	West			East		
	All sites	>6000 ft (>1830 m)	<6000 ft (<1830 m)	All sites	>7000 ft (>2100 m)	<7000 ft (<2100 m)
Decline in inches (cm) of SWE/decade	**-0.48 (-1.2)**	-0.36 (-0.91)	-0.45 (-1.1)	-0.33 (-0.84)	-0.29 (-0.74)	-0.35 (-0.89)
Decline (percent over the record)	**-19%**	-12%	-23%	-20%	-14%	-27%

In general, April 1 snow water equivalent in Montana has declined roughly 20% over the last 80 yr, and this decline is most pronounced at lower elevation sites.

[16] For more detail on our snowpack analysis methods see Appendix 3-2 on the MCA website.

Montana's snowpack is particularly sensitive to warming

Both empirical studies and model projections demonstrate that snowpack in the Northern Rockies and inland Pacific Northwest is more vulnerable to warming than some other regions in the West. For example, Mote and Sharp (2016) showed that western Montana and the Pacific Northwest have experienced the most drastic declines in snowpack volume in the West over the past 80 yr.

Unlike Rocky Mountain regions to the south, Montana stores a significant amount of snowpack at mid and low elevations (below 8000 ft [2400 m]), particularly within the Flathead, Kootenai, and lower Clark Fork basins of northwestern Montana. In regions such as these, the projected increase in temperatures will result in reduced winter snowpack and a higher-elevation snowline (Regonda et al. 2005; Klos et al. 2014).

Low elevations west of the Continental Divide are exposed to relatively warm Pacific air masses. These regions have experienced an increase in precipitation falling as rain instead of snow since the 1950s (Knowles et al. 2006), a trend that is expected to continue under future climate conditions (Barnett et al. 2005).

Snowpack projections for Montana

Here we present projections of April 1 SWE values for three of our focal snowmelt-dominated basins in Montana (Figure 3-10). Projections consist of two future scenarios of greenhouse gas emissions (Representative Concentration Pathways [RCPs], RCP4.5 and RCP8.5; see Climate chapter), for two periods in the future: 2040-2069 and 2070-2099. Model results were compared to a historical baseline period of 1970-2000. These projections highlight the general direction of projected changes and differences among watersheds across the state. Values near the dotted 0% line would represent model results that project no future change in snowpack relative to 1970-2000 data. While our results demonstrate relatively strong agreement among most of the climate models, they should only be used to project the direction of change and not specific future snowpack volumes.

April 1 SWE projections for RCP 4.5 and RCP 8.5 (2040-2069 and 2070-2099)

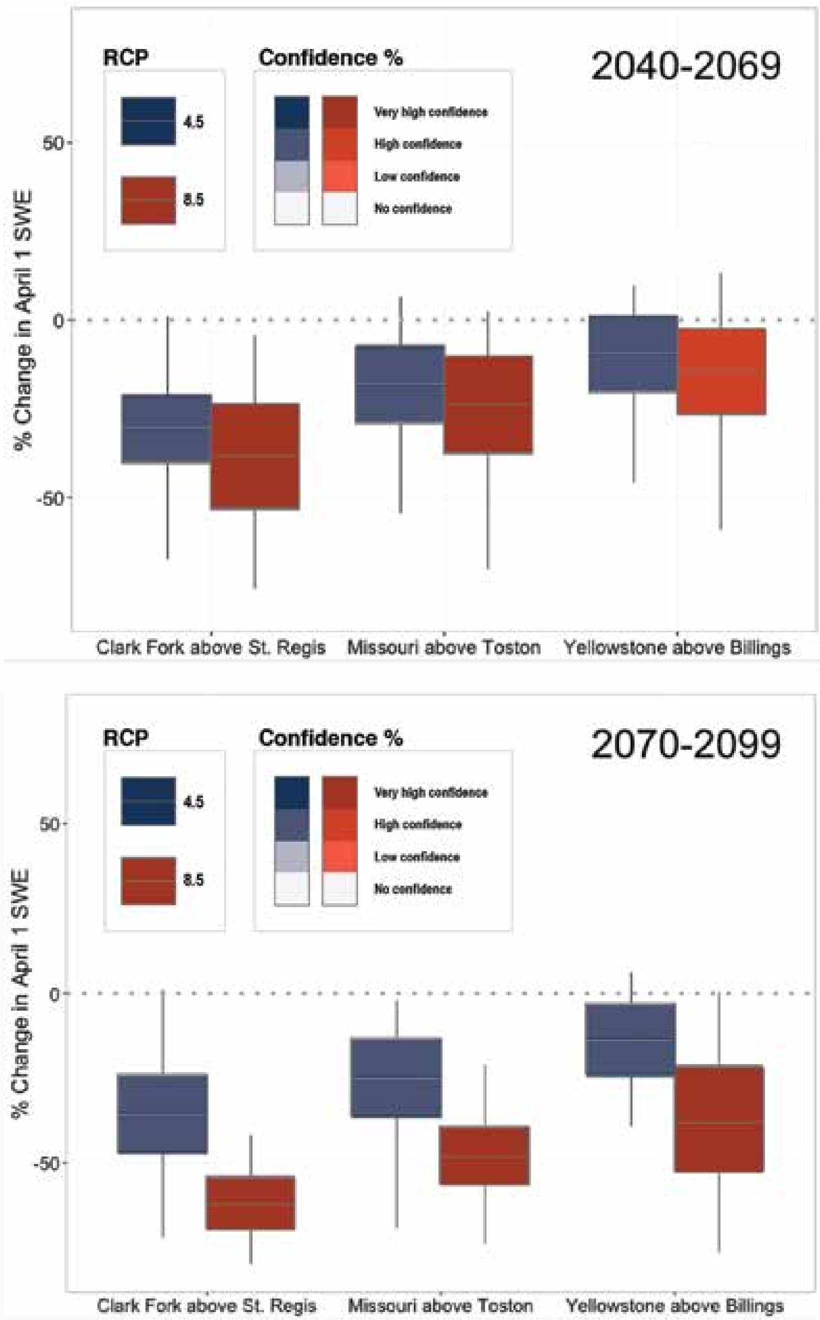


Figure 3-10. APRIL 1 SWE projections for three snowmelt-dominated basins in Montana under two scenarios (RCP4.5 and RCP8.5) and two time periods (2040-2069 and 2070-2099). Data are presented as the projected percent change in April 1 SWE between the baseline period 1970-2000 and two future time periods (2040-2069: upper panel; 2070-2099: lower panel). Box and whiskers plots show variation in projections among the different models. These types of plots appear in other graphs below that depict model projections.

The line in the middle of the boxplot represents the median value of all model projections. The bottom and top of the box represent the 25th and 75th percentiles (or first and third quartiles), respectively, of model projections. The upper whisker (line extending from the box) extends from the box to the largest model value no further than 1.5*IQR from the box (where IQR is the inter-quartile range, or distance between the first and third quartiles). The lower whisker extends from the box to the smallest model projection that is no further than 1.5*IQR of the hinge. Few model projections fall beyond the end of the whiskers (i.e., outliers), and these are not shown in the figures.

For explanation of specific confidence levels, refer to Future Projections in Water Chapter.

Our projections show that

- snowpack volumes for the Montana basins studied will very likely decline in the future; and
- the largest projected changes in snowpack appear to be located west of the Continental Divide, and are the same areas that have experienced the largest declines in April 1 SWE over the past 80 years (see, for example, the Clark Fork River in Figure 3-9).

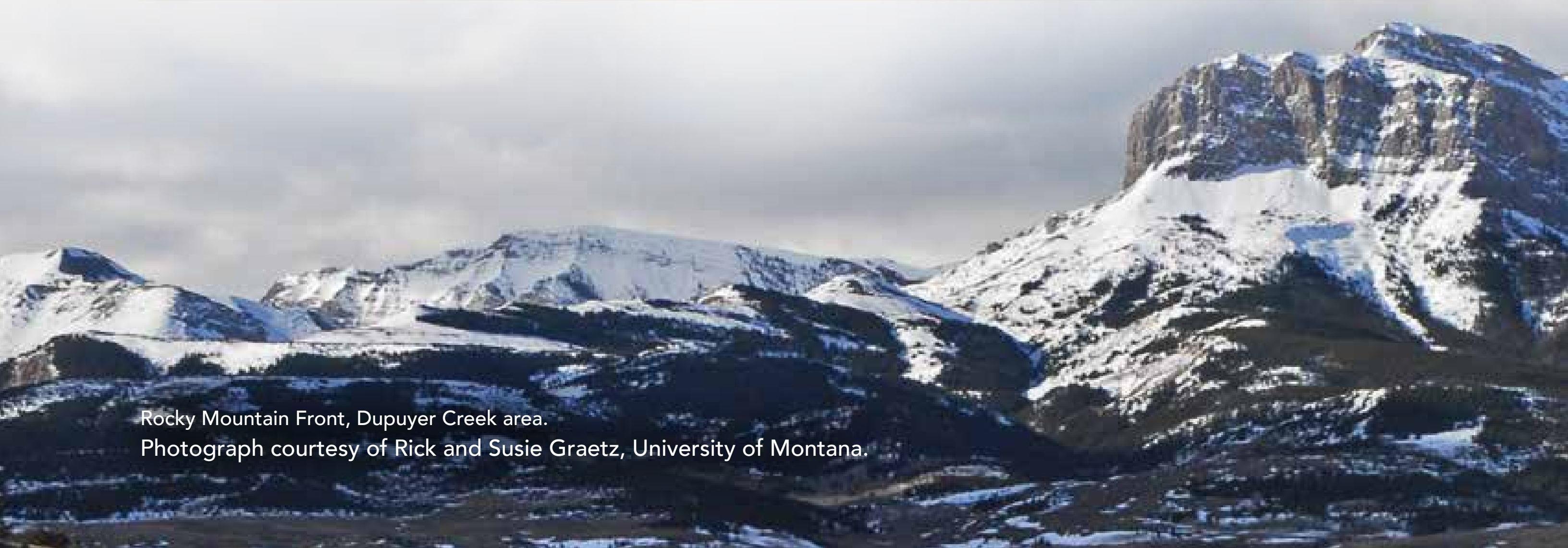
Small headwater basins west of the Continental Divide show this vulnerability because they occupy relatively low elevations that are likely to experience additional days with temperatures above the freezing point. In contrast, many small headwater basins east of the Continental Divide are at higher elevations (often 8000-10,000 ft [2400-3000 m]) and are thus less likely to experience temperatures above freezing during the winter-spring transition (see Climate chapter).

SNOWMELT AND RUNOFF TIMING

Key Messages

Historical observations show a shift toward earlier snowmelt and an earlier peak in spring runoff in the Mountain West (including Montana). Projections suggest these patterns are very likely to continue into the future as temperatures increase. [high agreement, robust evidence]

Earlier snowmelt and spring runoff will reduce late-summer water availability in snowmelt-dominated watersheds. [high agreement, robust evidence]



Rocky Mountain Front, Dupuyer Creek area.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

Changes in Montana's snowpack, as described in the previous section, have direct consequences for how water is delivered to streams and rivers, both in terms of amount and timing of runoff. Snowmelt runoff refers to snow and ice melting into liquid water, which eventually moves downhill and accumulates to produce streamflow. Snowmelt is a dominant component of the annual water cycle (Figure 3-1) in most mountain regions of the West, including Montana.

The majority of total annual streamflow volume in Montana rivers is delivered during a relatively short period in the spring, typically April through June. In the context of a changing climate, it is critical that we a) examine regional evidence for changes in snowmelt and runoff timing, b) assess what factors are most important in driving these changes, and c) evaluate observed and projected patterns in runoff timing for our focal rivers in Montana.

Observed regional trends in snowmelt and runoff timing

Researchers have already documented shifts toward earlier snowmelt and spring runoff in many mountain regions of the West (Figure 3-11) (Regonda et al. 2005; Stewart et al. 2005). Spring runoff has shifted at least a week earlier in the Northern Rockies over the past half-century, with most of this change occurring since the mid 1980s (Pederson et al. 2011a). Numerous studies in western North America support this conclusion (Dettinger and Cayan 1995; Stewart et al. 2004; McCabe and Clark 2005; Lundquist et al. 2009; Gillian et al. 2010), and some demonstrate that shifts in runoff timing have led to reduced streamflow during the summer months (e.g., Rood et al. 2008).

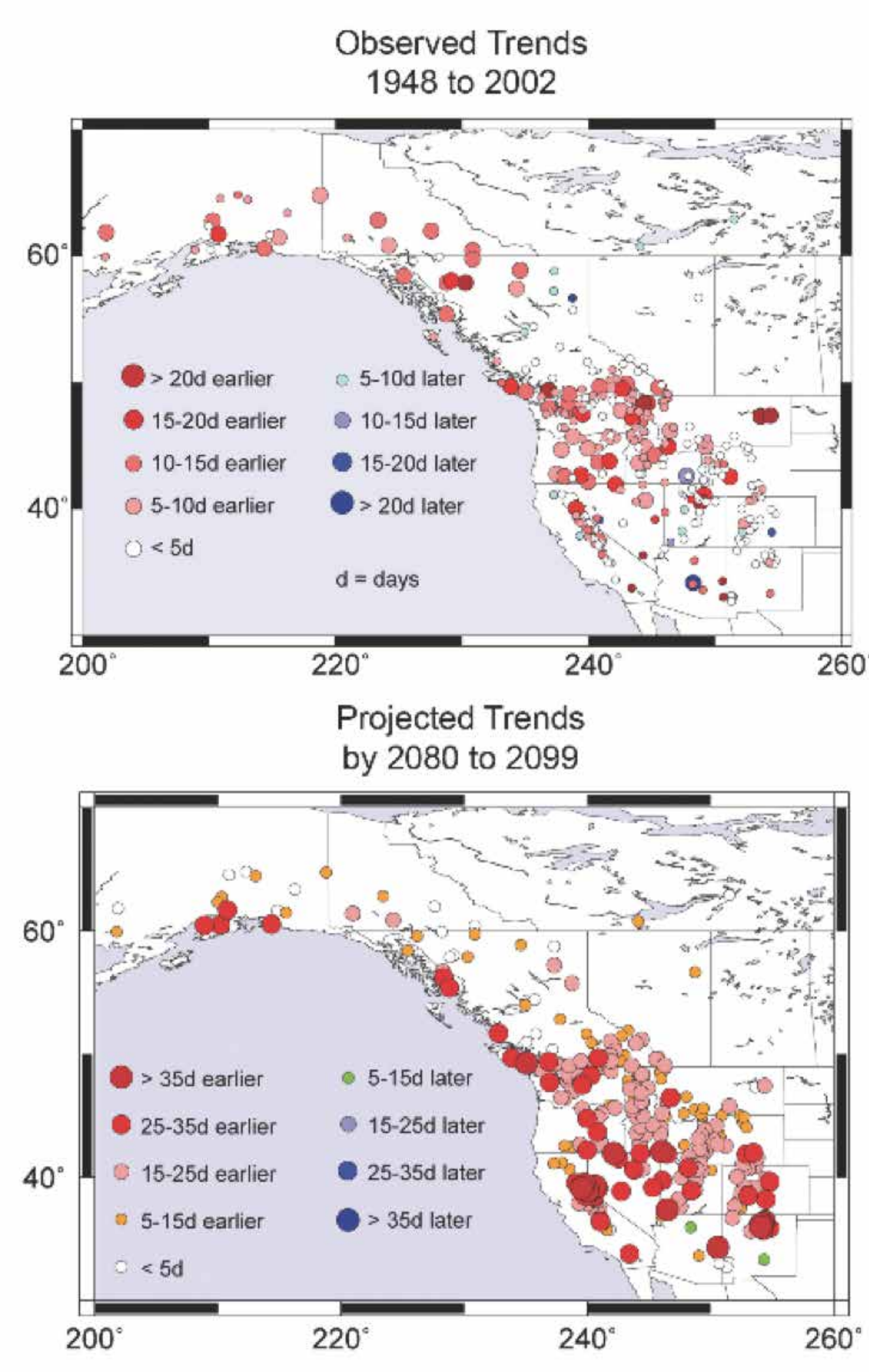


Figure 3-11. Observed and projected trends demonstrating a general shift toward earlier snowmelt and spring runoff in many regions of the west. Data represent observed and projected shifts in the center of timing[17] of streamflow. Projected trends in center of timing for 2080-2099 are compared to a baseline of 1951-1980 (Stewart et al. 2004).

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[17] *Center of timing* refers to the calendar date at which half the total annual volume of streamflow has passed a given streamflow gauging station.

Factors that influence snowmelt and the timing of runoff

Factors that influence snowmelt and the timing of runoff include temperature, precipitation, and elevation, as described below.

- Temperature.—There is evidence for a connection between warmer winter and spring temperatures and earlier timing of spring runoff for many rivers in western North America (Stewart et al. 2004). While some of this variation has been attributed to decadal-scale climate oscillations (e.g., Pacific Decadal Oscillation), much of it is linked to the trend of long-term warming in spring observed since 1948 (Das et al. 2009).

  Spring warm spells are occurring more frequently and earlier in recent years, and even modest warming in winter or spring can lead to large changes in snowmelt and runoff dynamics, especially at lower elevations (Regonda et al. 2005; Stewart et al. 2005; Klos et al. 2014).

  Rising winter and spring temperatures have already been observed in most regions of Montana since 1950 (see Climate chapter). Pederson et al. (2010) reported a rapid decline in the annual number of days below freezing in western Montana since the 1980s. In addition, from 1950-2015, spring maximum temperatures increased more than any other season (0.7°F/decade [0.4°C/decade]) (Pederson et al. 2010). Over the same period, winter minimum temperatures increased by approximately 0.6°F/decade (0.3°C/decade). Projections of statewide warming into the future (see Climate chapter) will advance snowmelt to earlier dates.

- Elevation.—Along with slope, aspect, and other features of the local setting, elevation is a critical variable that determines how watersheds across Montana respond to changes in climate because of the relationship between elevation and temperature (Pomeroy et al. 2004; Stewart et al. 2004; Bales et al. 2006; DeBeer and Pomeroy 2009; Lundquist et al. 2009; Pederson et al. 2010). Mid-elevation locations tend to be most sensitive to warming trends because small increases in temperature sometimes result in temperatures rising above freezing, which is less likely at higher (and thus colder) elevations. Regonda et al. (2005) showed that from 1950-1999 spring runoff has come 10-20 days earlier in basins below 8000 ft (2400 m) elevation, while basins above this elevation have shown little to no change in runoff timing. Thus, for Montana, changes in snowmelt timing should be more pronounced for areas west of the Continental Divide and low-elevation sites east of the Continental Divide that contribute to winter snowpack.

- Precipitation.—Observed changes in precipitation across Montana since 1950 are more varied and uncertain when compared to the strong evidence for ongoing and continued increases in temperature. However, there has been a general trend of decreasing winter precipitation from 1950 to present; this pattern is most evident in the northwest and central portions of the state and may be due to increased frequency of El Niño events (see Climate chapter). Natural variation in precipitation influences snowmelt timing and the seasonal distribution of streamflow. For example, below-average winter precipitation can lead to smaller mountain snowpack volumes, which tend to result in shorter duration spring runoff (Hamlet and Lettenmaier 1999; Stewart et al. 2004; Moore et al. 2007; Whitfield 2013). Warming temperatures can also result in more precipitation falling as rain instead of snow, particularly in the Pacific Northwest and western Montana (Knowles et al. 2006), also resulting in reduced snowpack and shorter duration runoff (Knowles et al. 2006; McCabe et al. 2007; Gillian et al. 2010; Knowles 2015). Conversely, particularly high-snowpack years may effectively compensate for warming temperatures by offsetting rapid snowmelt. Spring precipitation as rain or snow can also help to augment years of relatively low winter snow and prevent reduced streamflow. Indeed, increased spring precipitation in recent years has apparently prevented what would otherwise be large snow-related declines in hydrologic yield (Pederson et al. 2011a). In addition, year-to-year fluctuations in spring precipitation may be contributing to variation in the timing of runoff among years (Pederson et al. 2011a).

North Fork Flathead, Glacier National Park.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

Model projections for snowmelt and runoff timing

Strong agreement exists among climate models that average temperatures will continue to increase through the mid century (2040-2069) and end-of-century (2070-2099) across Montana (see Climate chapter). The climate models also project an increase in precipitation during winter, spring, and fall, but the magnitude of this change is small relative to historical variation and there is less agreement among models.

We used the same model output described in the snowpack section to assess projected changes in streamflow for our focal river basins. Hydrologic models include uncertainty related to the GCMs selected for the model, as well as uncertainty related to projected future change in elements of the water cycle, such as evapotranspiration. Additionally, all of these models were run without consideration of human water use, which will need to be incorporated to effectively manage water resources (see Missouri River sidebar). Therefore, these projections should not be considered specific predictors of future streamflow volumes, but instead as a useful tool for understanding the general direction (positive or negative) of change.

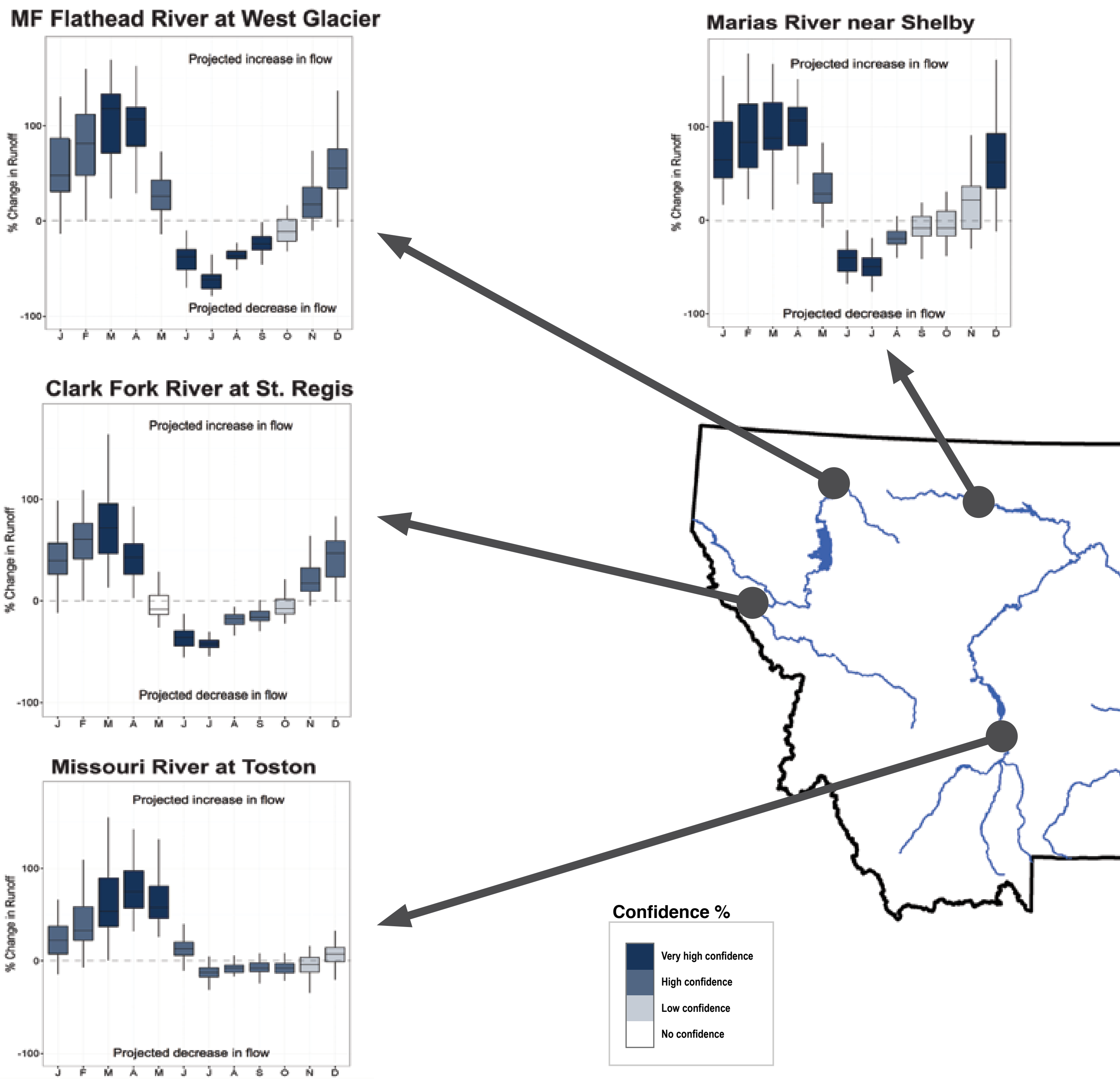
Two distinct patterns of projected streamflow emerge from our analysis, one from watersheds that contain large amounts of land at high elevations and the other from those that do not (Figure 3-12).

In watersheds with headwaters at relatively high elevations—for example, the Yellowstone at Billings, Missouri at Toston, Clark Fork at Saint Regis, and Marias at Shelby—the models show strong agreement that a) January-April runoff is likely to increase, and b) streamflows will likely be reduced during July-September (Figure 3-12). Although the different projections show slight differences in timing among rivers, the overall patterns are consistent: a larger percentage of water will leave these watersheds during winter and early spring, resulting in much less water to support streamflow during summer and early fall. The shift is important given the high demand for water resources in late summer from agriculture, municipalities, and recreation industries.

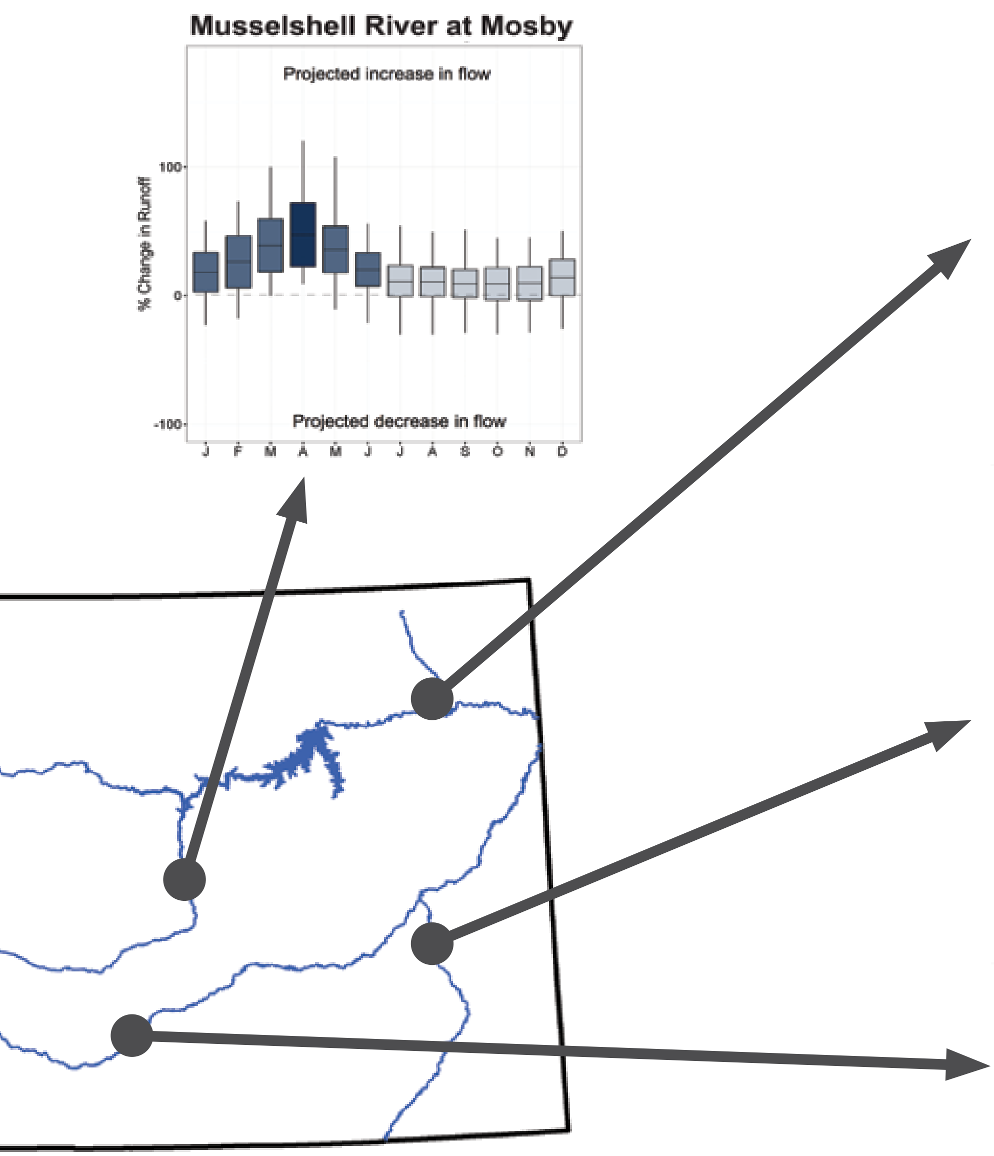
For watersheds with high-elevation headwaters, the overall patterns in model projection are consistent: a larger percentage of water will leave high elevations during the winter and early spring, leaving much less water to support streamflow later in the year during summer and early fall.

Projections for middle-to-low-elevation watersheds—for example the Musselshell at Mosby, Powder River near Locate, and Poplar River near Poplar—show similar increases in winter and spring streamflow (i.e., most of the projections fall above the 0 line). However, the models agree far less about streamflow patterns during the rest of the year (Figure 3-12), with some projecting increases in streamflow in summer and fall, while others project reduced streamflow during these months.

Monthly Streamflow Projections for RCP 8.5 (2040-2069)



It is very likely that increased water use in the future will further reduce streamflows during summer months when demand is greatest (see drought section below).



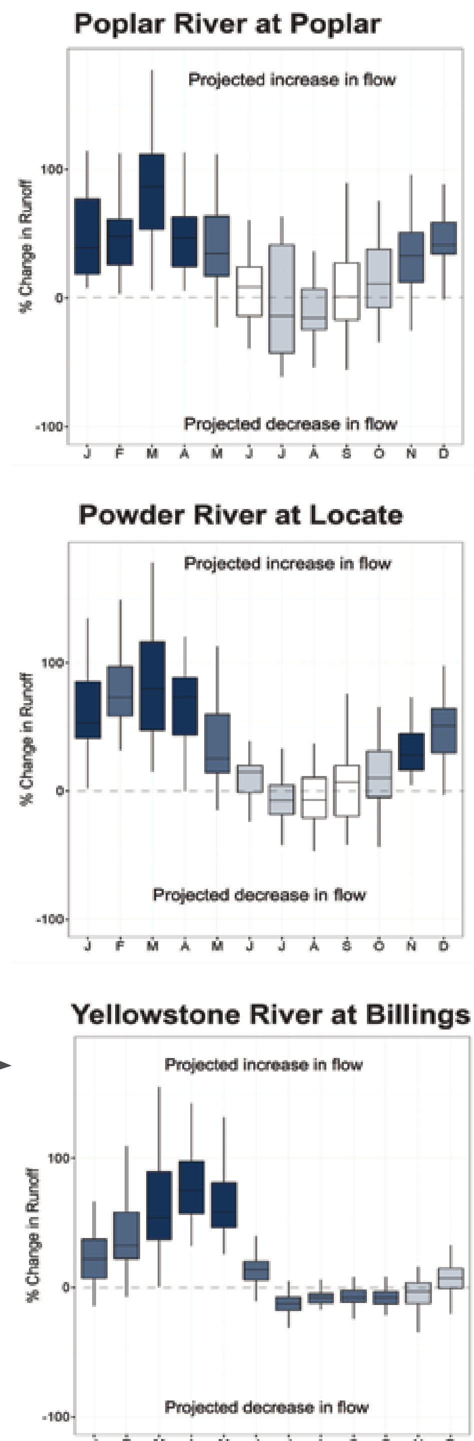


Figure 3-12. Monthly streamflow projections for each of our focal rivers based on RCP8.5 and time period 2040-2069. Data are presented as the projected percent change in runoff between 2040-2069 and the baseline period of 1970-2000. (Boxplots are explained in the caption of Figure 3-10.) For explanation of specific confidence levels, refer to Future Projections in Water Chapter.

TOTAL ANNUAL STREAMFLOW

Key Messages

Long-term (decadal and multi-decadal) variation in total annual streamflow is largely influenced by quasi-cyclic changes in sea-surface temperatures and resulting climate conditions; the influence of climate warming on these patterns is uncertain. [high agreement, medium evidence]

Total annual streamflows are projected to increase slightly for most Montana rivers, but the magnitude of change and agreement among models vary across the state. [medium agreement, medium evidence]

To this point, our streamflow discussion has focused on how climate influences the timing and distribution of flow throughout the year. However, it is also important to consider patterns of annual streamflow (or annual water supply), which is the total amount of runoff generated by a given watershed throughout an entire year.

Annual streamflow derives from a variety sources including rainfall, snowmelt runoff, groundwater discharge, and glacial runoff. Annual streamflow is critical because it defines the potential volume of water available each year to influence groundwater, fill reservoirs and lakes, and support consumptive and non-consumptive uses of water. Climate-induced changes in annual streamflow have the potential to impact hydroelectric power generation, agricultural production, wildlife habitat, recreation, and other beneficial uses of Montana's water resources.

Long-term records demonstrate that annual streamflow varies widely over time due to changes in both natural and human-related factors. Here again, we focus largely on atmospheric processes that influence annual streamflow (i.e., temperature and precipitation), which are themselves modified by both natural and human-related factors, such as greenhouse gas emissions.

Interannual variation in precipitation tends to have the greatest influence on year-to-year variation in annual streamflow volumes (Karl and Riebsame 1989; McCabe and Wolock 2011). Years of high snowpack accumulation or high spring and summer rains tend to produce high annual streamflow volumes and hence greater potential water supply. While temperature effects on annual streamflow are much weaker and less consistent than the effects of precipitation, the relative importance of temperature is likely to increase as the climate warms (Tesemma et al. 2015; Woodhouse et al. 2016).

Observed trends in total annual streamflow

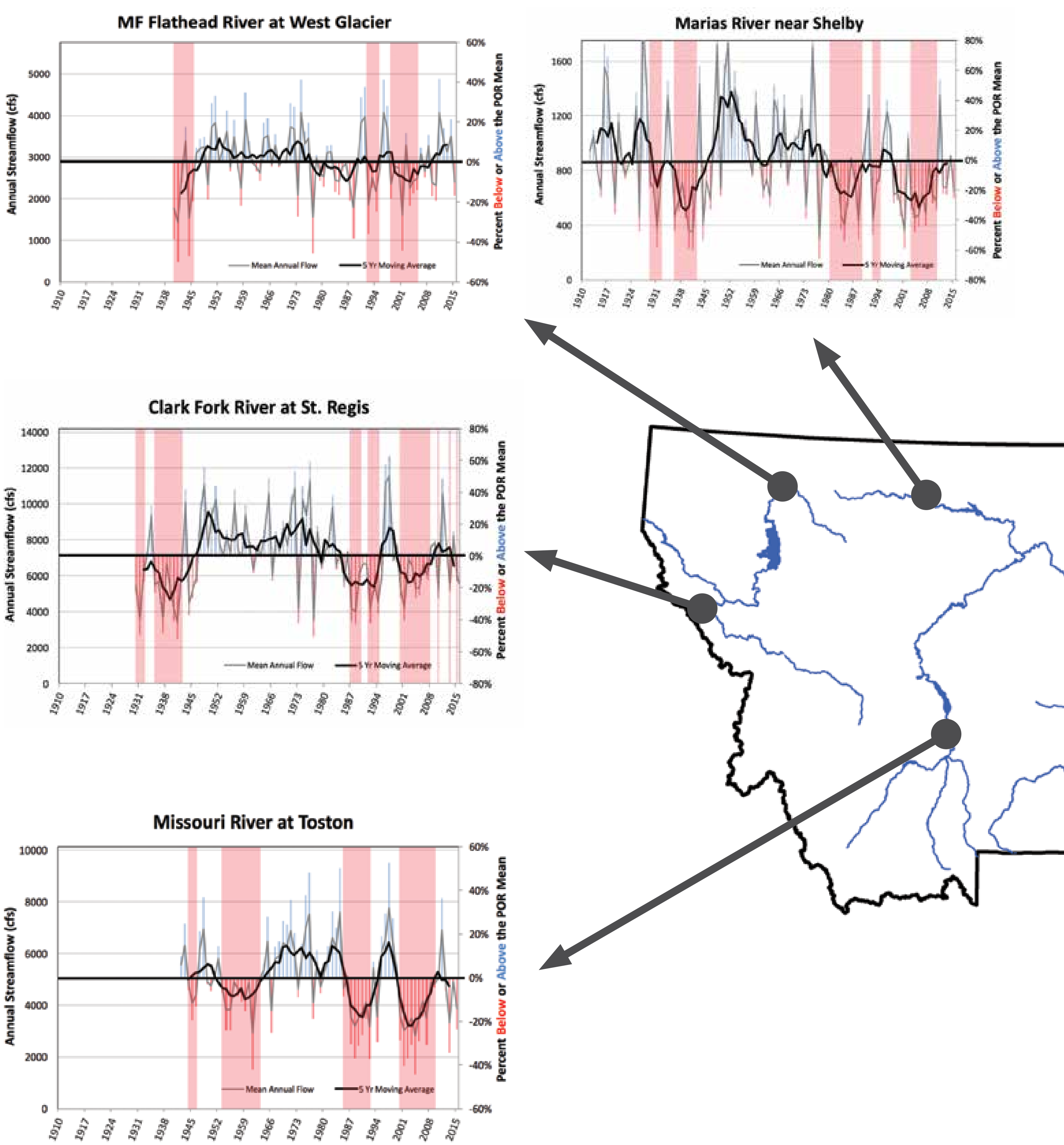
On decadal time scales, annual streamflow variation and precipitation are driven by large-scale patterns of climate variability, such as the Pacific Decadal Oscillation (see teleconnections description in Climate chapter) (Pederson et al. 2011a; Seager and Hoerling 2014). Periods of high or low precipitation associated with these patterns generally translate to periods of high or low annual streamflow, respectively (Karl and Riebsame 1989; McCabe and Wolock 2011). Obvious periods of lower-than-average streamflow in most of the focal rivers in Montana include the drought years of the Dust Bowl (late 1920s to early 1940s), the 1950s, the late 1980s to early 1990s, and the early 2000s (Figure 3-13).

Specific years of above- and below-average streamflow differ slightly among river basins due to Montana's geographic diversity and the varying influence of large atmospheric circulation patterns east and west of the Continental Divide. Interestingly, large semi-cyclic patterns in total annual streamflow are detectable in most Montana rivers, suggesting that parallel changes in water use over time have not been large enough to mask these climate-driven trends. Such patterns in annual streamflow, however, are often hidden for rivers that are highly regulated by dams or large irrigation withdrawals (e.g., the Marias River below Tiber Reservoir) (MT DNRC 2014c).

A key question is whether annual streamflows have changed over time in Montana and, if so, why. Pederson et al. (2011b) reported no recent change in annual streamflow for a number of rivers in the northern Rocky Mountains, including in Montana, despite significant reductions in snowpack. The authors attributed this finding to recent increases in spring precipitation that may have offset reduced snowpack.

Luce and Holden (2009) reported declines in annual streamflow during the driest years (i.e., lowest 25th flow percentile) for a set of Pacific Northwest rivers, including some rivers in Montana west of the Continental Divide. Other work has suggested that streamflow declines in the Pacific Northwest have resulted from reduced mountain precipitation rather than warming (Luce et al. 2013).

Long-term Patterns of Annual Streamflow



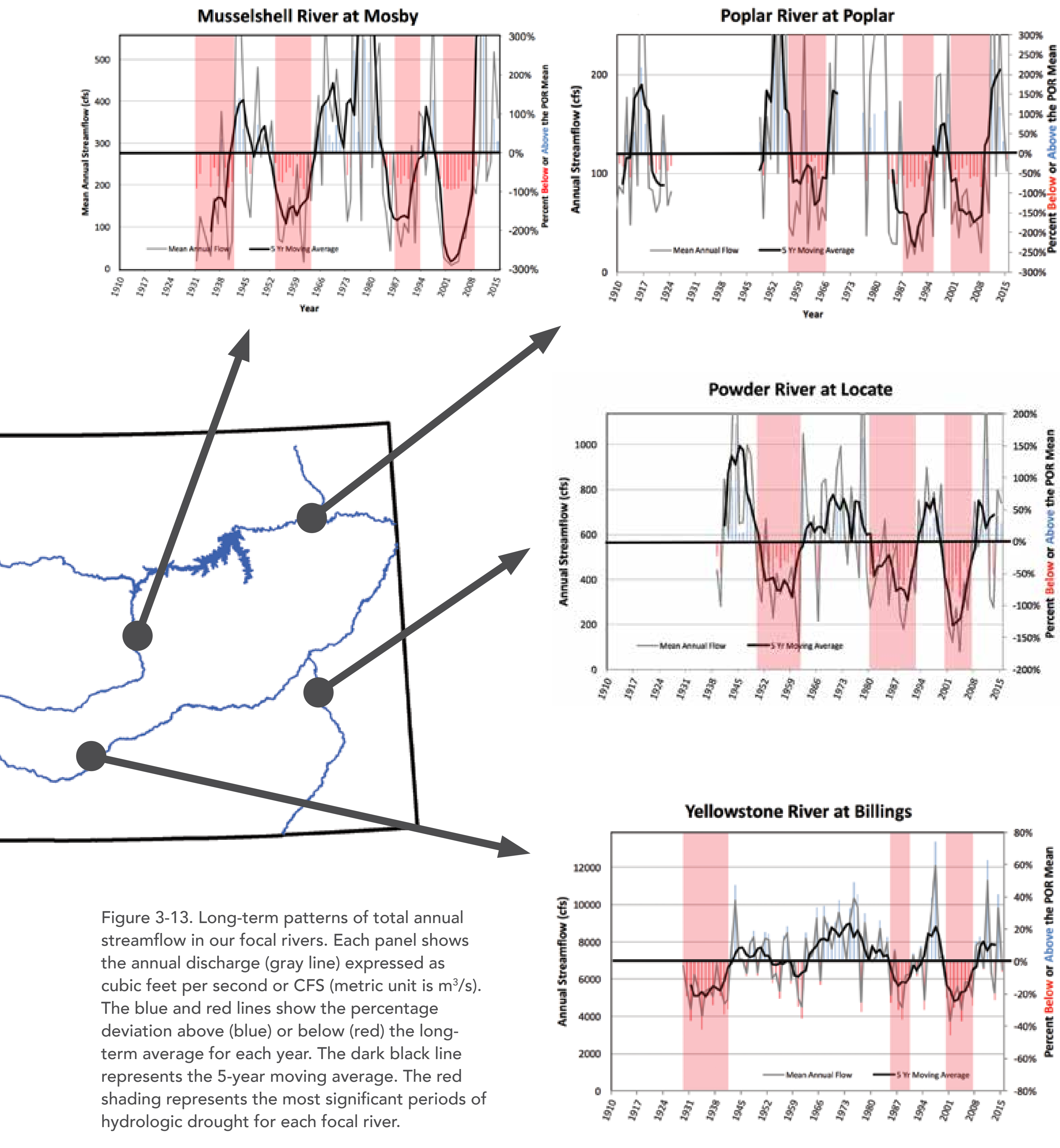


Figure 3-13. Long-term patterns of total annual streamflow in our focal rivers. Each panel shows the annual discharge (gray line) expressed as cubic feet per second or CFS (metric unit is m^3/s). The blue and red lines show the percentage deviation above (blue) or below (red) the long-term average for each year. The dark black line represents the 5-year moving average. The red shading represents the most significant periods of hydrologic drought for each focal river.

Norton et al. (2014) also reported recent (1960-2010) declines in annual streamflow for 30 rivers in the Upper Missouri watershed. It is unclear whether these declines are attributed to changes in climate or other factors such as changing patterns of land or water use (e.g., conversion of agricultural lands to subdivisions, or changing irrigation methods and practices).

Factors that influence total annual streamflow

At local scales and over shorter periods, annual streamflow responds to seasonal changes in climate variables (e.g., temperature, precipitation) and related processes such as evapotranspiration. The relative influence of these factors on annual streamflow differ across the state's watersheds. Thus, identifying the most important factors that influence annual streamflow in each basin can help us understand how changing climate may influence future water supplies.

Analysis for the Upper Missouri River Headwaters Study quantified climate factors impacting annual streamflow variability for a number of important watersheds in Montana (USGS undated; analysis contributed by Connie Woodhouse, University of Arizona). The work, which covered 1936-2010, considered average monthly temperatures and total monthly precipitation for the water year (prior October to September) as possible predictors of annual streamflow. Importantly, this particular analysis was conducted with streamflow data corrected for water use and human modification (i.e., naturalized flows). Thus, these results provide a window into the direct climate factors that impact streamflow. A summary of results explaining interannual variability of streamflow follows.

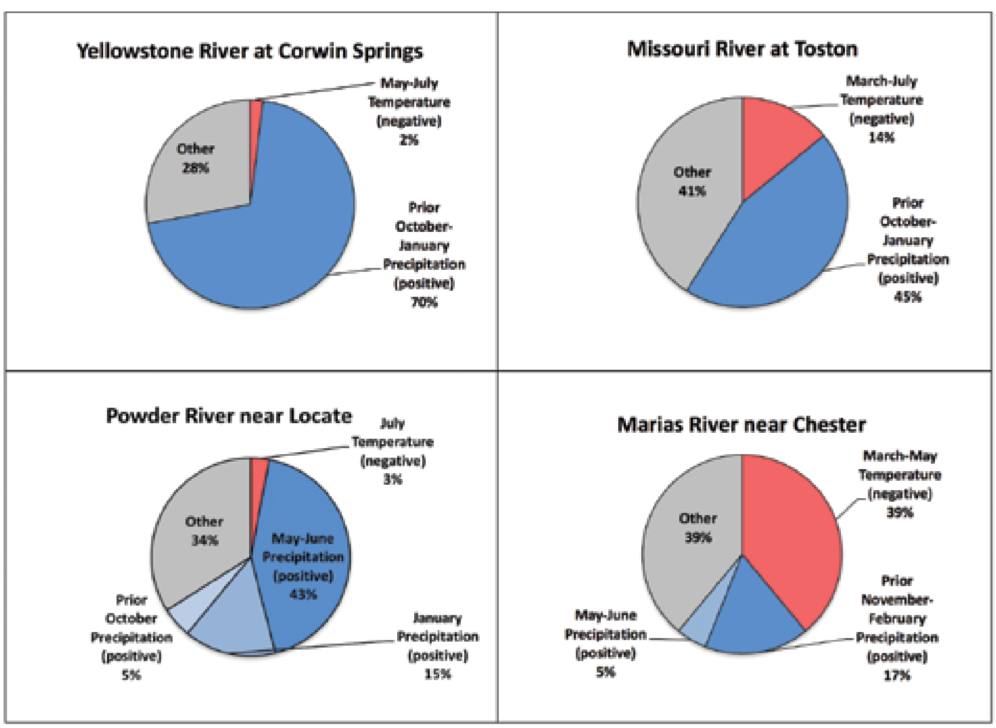


Figure 3-14. Climate factors associated with naturalized streamflow in four Montana river basins. The size of pie pieces correspond to how strong the particular climate factor influences total annual streamflow. Some of these factors lead to greater flow (positive), while others lead to reduced annual flow (negative). See text for further explanation.

- For the Missouri River at Toston, fall-to-early-winter (October-January) precipitation accounts for nearly half (45%) of the variability in total annual streamflow (Figure 3-14).[18] Years of high winter precipitation lead to years of high annual streamflow. Snowmelt season (March-July) temperatures explain an additional 14% of the interannual variation in flow, likely because warmer temperatures during this time can lead to greater evapotranspiration and reduced annual streamflows.

- In contrast, for the Marias River basin near Chester,[19] spring-to-early-summer temperatures, not fall-to-winter precipitation, account for the largest amount (40%) of annual streamflow variation (Figure 3-14), although reasons for this observation are not entirely clear. Prior November-January precipitation is the second most important factor (17% of the variation), with spring-early summer (May-June) precipitation being third (5%).

- For the Powder River near Locate, May-June precipitation accounts for close to half (43%) of the annual variability in streamflow, probably because southeastern Montana receives the majority of its annual precipitation in the spring and early summer. January precipitation accounts for 15% of annual variation, showing that winter precipitation from the Powder River's alpine headwaters in Wyoming is also important.

- For the Yellowstone River at Corwin Springs,[20] at the northern edge of Yellowstone National Park, fall and early winter precipitation (Oct-Jan) account for 70% of the annual variability. Runoff season temperatures have a minimal effect on annual flow, perhaps because much of the watershed consists of high-elevation terrain and snowpack that is less affected by variation in spring temperatures.

The Missouri River analysis suggests that large snow years that are associated with cold air temperatures during runoff lead to the greatest annual water supplies. The Marias River analysis suggests that rising spring temperatures could exacerbate low flows in the Marias during years of below-average precipitation. All analyses include significant other variation that remains unexplained, suggesting that a) the models do not include all factors influencing annual streamflow, and b) there is some observational and statistical error.

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[18] For an explanation of methods see Appendix 3-2 on the MCA website.

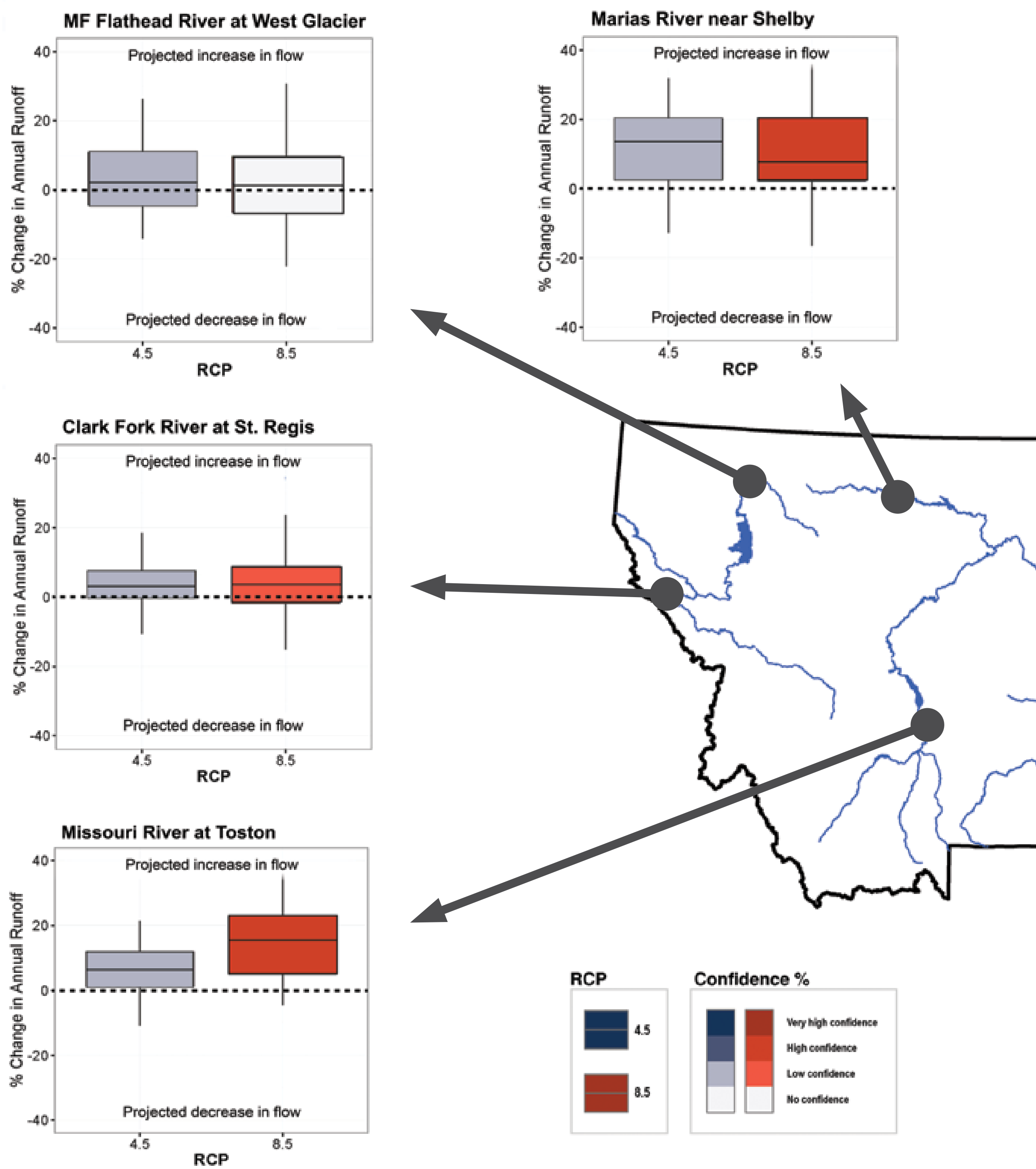
[19] Marias at Chester is the closest downstream gage to Marias at Shelby, one of our focal gages. Gages in this particular analysis were selected by the Basin Study of the Missouri River watershed (see earlier sidebar).

[20] Yellowstone at Corwin Spring is not one of our focal rivers, but it is included here to show additional variation in drivers of annual flow.

Annual streamflow projections

Model projections for annual streamflow (Figure 3-15) show little agreement among models regarding the direction and magnitude of change in our two focal rivers west of

Annual Streamflow Projections for RCP 4.5 and RCP 8.5 (2040-2069)



the Continental Divide (Middle Fork of the Flathead and Clark Fork at St Regis). In contrast, projections show moderately-high to high agreement that total annual streamflow will increase east of the Continental Divide (e.g., Missouri River, Yellowstone River, Musselshell River), especially under the RCP8.5 emission scenario (see Climate chapter).

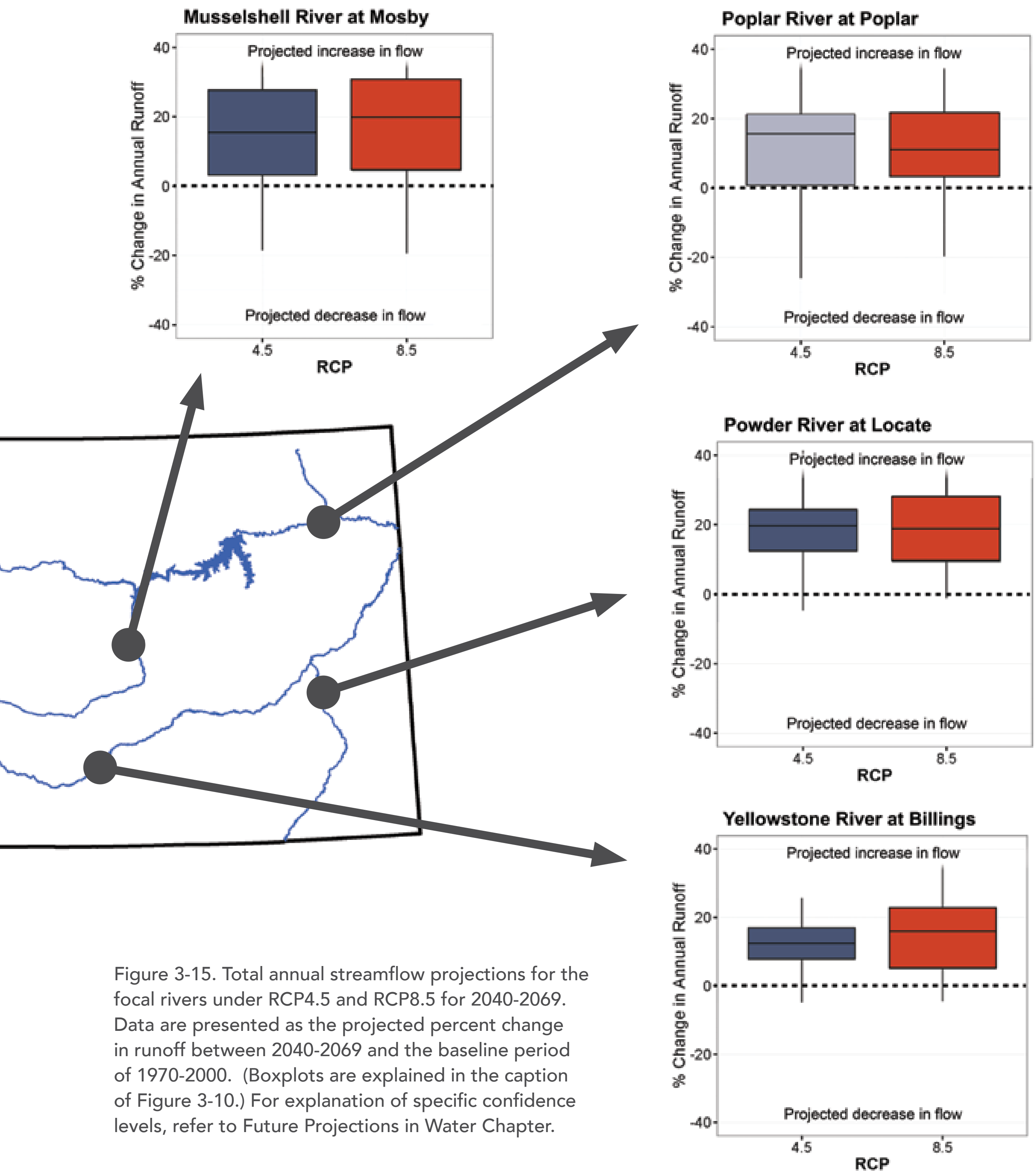


Figure 3-15. Total annual streamflow projections for the focal rivers under RCP4.5 and RCP8.5 for 2040-2069. Data are presented as the projected percent change in runoff between 2040-2069 and the baseline period of 1970-2000. (Boxplots are explained in the caption of Figure 3-10.) For explanation of specific confidence levels, refer to Future Projections in Water Chapter.

GROUNDWATER

Key Messages

Local responses of groundwater resources to climate change will depend on whether aquifers are directly sensitive to climate variability, are buffered from climate by water-use practices such as irrigation, or are used to meet water demands that exceed or replace surface water supplies. [high agreement, robust evidence]

Groundwater demand will likely increase as increasing temperatures and changing seasonal availability of traditional surface water sources (i.e., dry stock water ponds or failure of canal systems to deliver timely water) force water users to seek alternatives. [high agreement, medium evidence]

Groundwater—water that is stored and transmitted in aquifers below the Earth's surface—is a crucial but hidden part of the water cycle. On a global scale, groundwater represents 96% of available freshwater (excluding polar and glacier ice). Groundwater is one of Montana's most valuable natural resources: a) it is often the only source of water for domestic use outside of municipalities, either for individual homes or small public water supplies; b) it provides water for livestock production and agriculture in the certain parts of the state; and c) it plays a critical role in sustaining streamflow throughout the year (in a typical Montana stream, groundwater contributes 50% of the annual flow [MT DNRC 2015]).

Montana's aquifers are closely tied to the geology of the state's two prominent geographic regions (Figure 3-16):

- The intermontane basins of the northern Rocky Mountains.—Within these basins groundwater generally occurs in shallow alluvial (sand and gravel) aquifers, and in deep-confined to semi-confined basin-fill aquifers, both of which contain large amounts of water.
- The northern Great Plains of eastern Montana.—Aquifers in this region are not as productive, but groundwater is nonetheless highly utilized. Layers of sedimentary sandstone and limestone form the most important aquifers. Alluvial aquifers within major river valleys are more localized, but also important.

Each geographic region has a unique climate, geology, and geologic history; these, in turn, have created the different hydrogeologic settings and determine the location and size of groundwater.

Figure 3-16. Montana is divided into two physiographic regions: the intermontane basins of the northern Rocky Mountains, and the northern Great Plains of eastern Montana.

Water moves between the surface and subsurface (groundwater) in response to hydrostatic forces, as follows:

- Groundwater recharge (water movement from surface to subsurface) results from precipitation and/or through interaction with surface-water bodies (e.g., rivers and lakes). In the snowmelt-dominated intermontane basins of western Montana, groundwater recharge mechanisms include: 1) diffuse movement of precipitation and snowmelt through soil to groundwater, 2) focused gains of water from ephemeral or perennial streams, especially along mountain fronts, and 3) percolation of excess irrigation water below canals and fields. In the large sedimentary aquifers of eastern Montana, groundwater recharge is principally by 1) focused recharge through streambeds, and 2) diffuse infiltration of precipitation in rocky outcrop areas.
- Groundwater discharge (water movement from subsurface to surface) is the loss of water from an aquifer to wells, surface water, or the atmosphere, driven by human and natural processes.

Residence times for groundwater can range dramatically, from days in shallow alluvial aquifers to tens of thousands of years in deep bedrock aquifers. Residence time is one of the factors that can affect an aquifer's sensitivity to climate change. Groundwater systems with longer residence times may be less impacted by a changing climate than those with short residence times.

In Montana, more than 200,000 wells withdraw about 875 acre-feet/day (1.1x106 m^3/day) for stock, irrigation, industrial, domestic, and public water supply uses (Figure 3-17) (MBMGa undated). In Montana's rural areas, groundwater supplies stock, ranch, and domestic needs. In some of Montana's more urban areas—for example, Missoula, Kalispell, and Sidney—groundwater is *the* public water supply source.

Groundwater also plays a crucial role in sustaining streamflow throughout the year. About half of the total annual flow in typical Montana streams derives from groundwater (MT DNRC 2015).

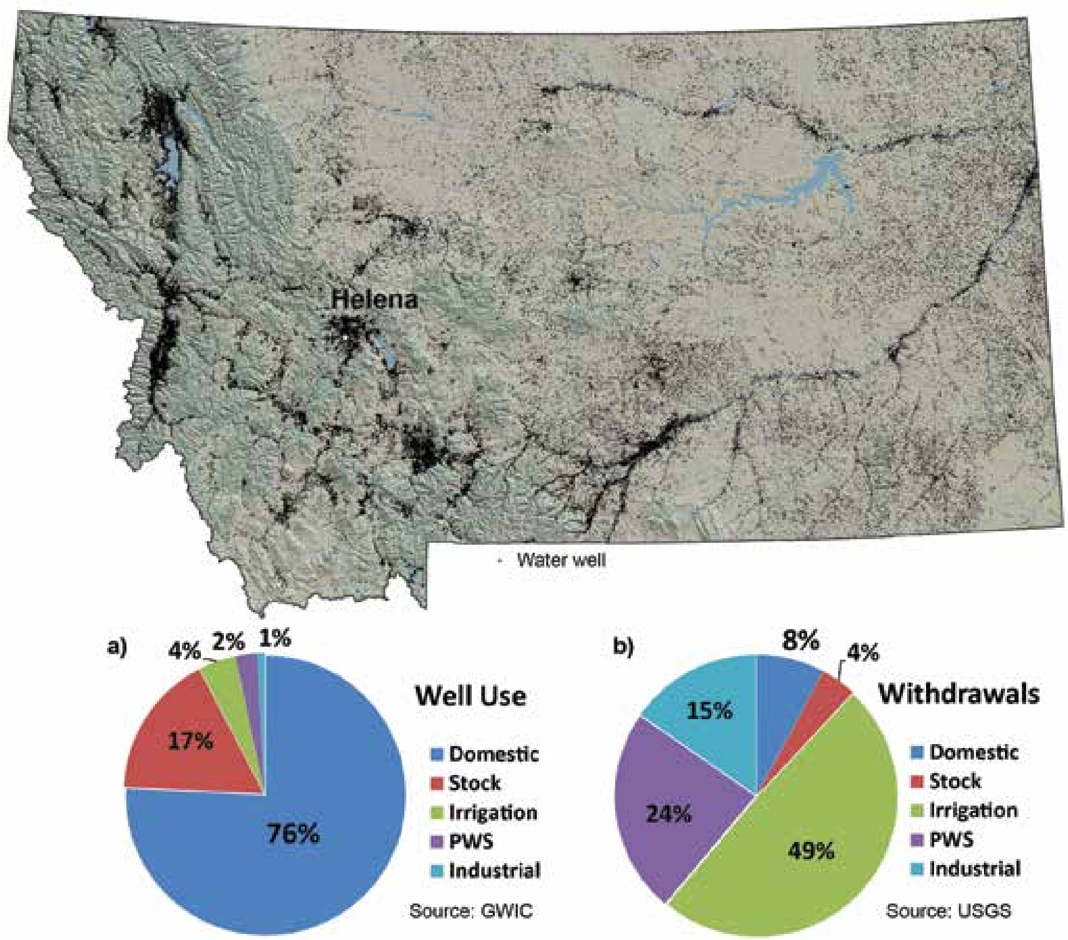


Figure 3-17. There are roughly 200,000 wells (tiny black dots in figure) that provide water for a variety of uses: a) most wells are for domestic and stock use; b) most withdrawals are for irrigation and public water supply.

The effects of climate change on groundwater resources are relatively uncertain, but the sensitivity of a given aquifer to change will depend on its geographic setting, and the particular mechanisms of groundwater recharge. Projected climate change is likely to reduce recharge, increase water demand, and alter interactions between groundwater and surface-water systems (Earman and Dettinger 2011; Green et al. 2011; Huntington and Niswonger 2012; Taylor et al. 2013). Reductions in recharge are expected for mountain aquifer systems because of decreased snowpack and changes to patterns of infiltration. The gradual character of snowmelt is more favorable to infiltration than rainfall events; therefore, as an increasing percent of precipitation falls as rain instead of snow, infiltration is likely to decrease, despite projected increases in winter and spring precipitation. Rising temperatures will also lead to a longer growing season, in turn increasing evapotranspiration and further reducing recharge (Meixner et al. 2016) (see Climate chapter). These expected reductions in recharge might appear contrary to projected increases in annual streamflow (Figure 3-15). However, changes in the character of precipitation (e.g., shifts from snow to rain or increases in extreme precipitation events) may cause more water to run off into streams and less to infiltrate into groundwater aquifers. Thus, surface water contributions and annual flow in a particular watershed may increase, even as recharge and baseflow contributions to streamflow decline.

In the sections that follow, we review groundwater information from three representative Montana aquifer systems (MBMGa undated). The data show how these systems have differentially responded to historical climate variability, which in turn provides insight into how groundwater resources might respond to future climate variability.

Madison Limestone—an aquifer sensitive to changes in climate

The Madison Limestone is a bedrock aquifer that underlies most of central and eastern Montana. The formation outcrops in the Little Belt and Big Snowy mountains of central Montana, where precipitation as snow and rain infiltrates into the groundwater system. Away from the mountains, hundreds of feet of non-aquifer, impermeable shale formations separate the Madison Limestone from the surface. However, where limestone layers are within 500-900 ft (150-270 m) of the land surface, the Madison Limestone aquifer is a productive and important source of domestic, municipal, industrial, and stock water. The aquifer is the source for many large springs, including Giant Springs at Great Falls and Big Springs at Lewiston.

In Cascade County, between the Little Belt Mountains and the Missouri River near Great Falls, more than 900 relatively low-use wells use the Madison Limestone aquifer (Figure 3-18). Between 1995 and 2005, water levels in Madison Limestone aquifer observation wells near Great Falls dropped by about 30 ft (9 m), while the number of Madison Limestone-aquifer wells nearly doubled from about 400 to 800 (Figure 3-19) (MBMGb undated).

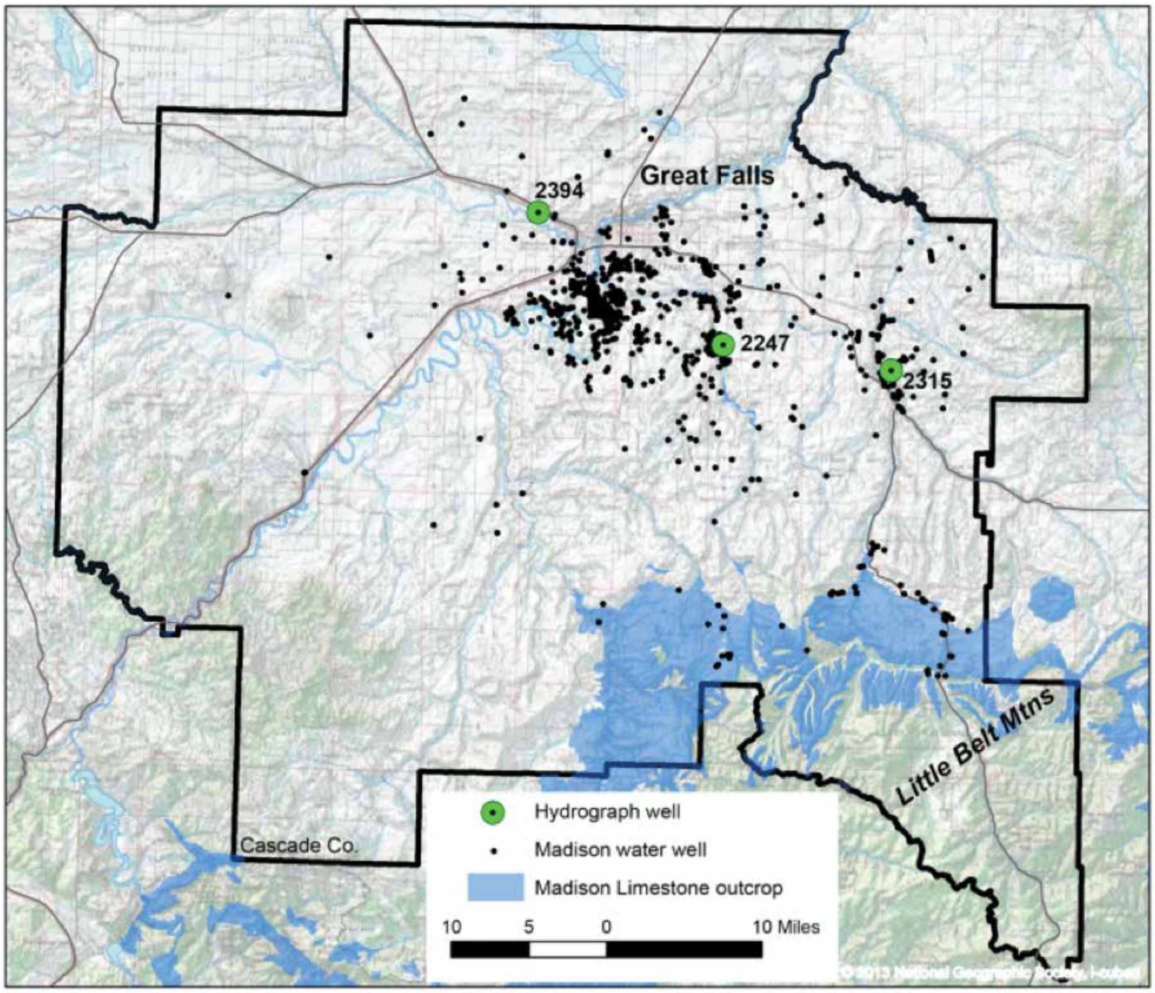


Figure 3-18. More than 900 wells (black dots) obtain water from the Madison Limestone aquifer near Great Falls. The Madison Limestone is exposed at the surface in the Little Belt Mountains (blue area on map), but is more than 400 ft (120 m) below the surface at Great Falls (MBMGb undated).

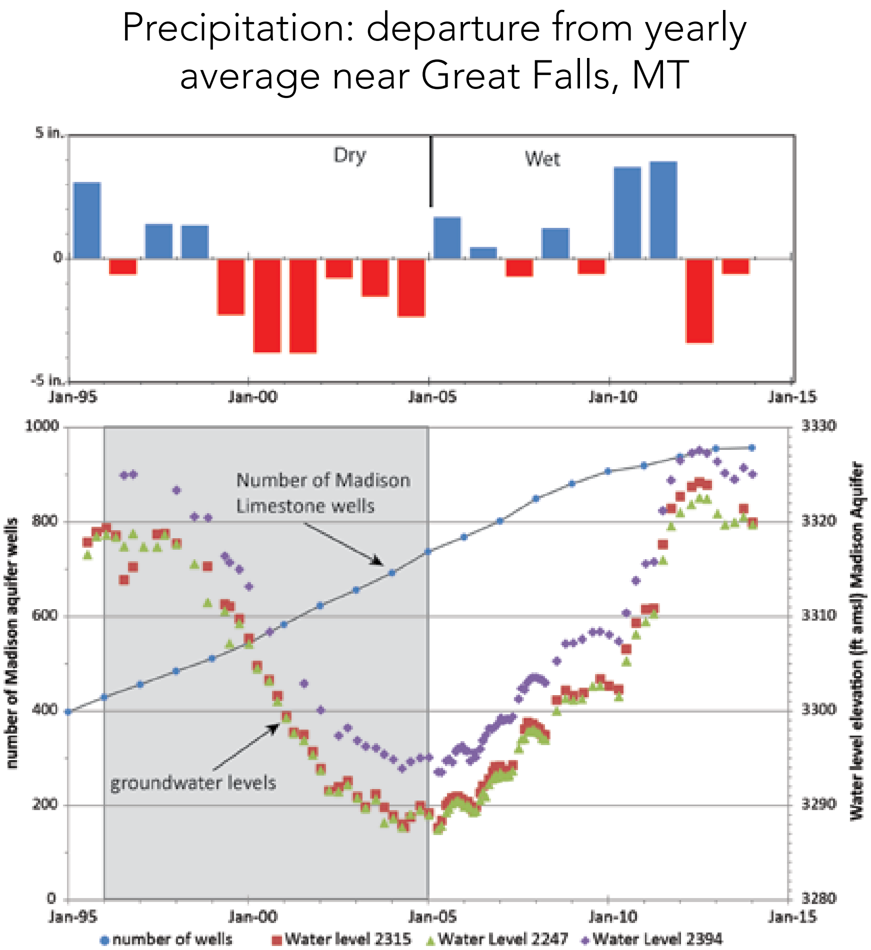


Figure 3-19. Between 1995 and 2005, the number of wells drilled into the Madison Limestone aquifer around Great Falls nearly doubled. During the same period, water levels in the aquifer dropped by 30 ft (9 m). However, this was also a dry period, as indicated by the departure from average precipitation plot above. Water levels recovered following several wet years, even though wells continued to be drilled into the aquifer. Location of the hydrograph wells is shown in Figure 3-18.

The decrease in water levels from 1995-2005 suggested that wells were removing water from the aquifer faster than it was being replenished. However, since 2005 water levels have climbed to elevations *higher* than those in 1995 even though new wells continued to be drilled into the Madison Limestone aquifer. This increase in water levels matches an increase in precipitation observed during that same period (Figure 3-19) and suggests that climate—and specifically mountain precipitation—as and is the primary driver of Madison Limestone aquifer water levels (i.e., groundwater replenishment and storage). The average annual precipitation from 1995-2005 was below average, supporting that conclusion. If small domestic withdrawals continue to characterize use in the Madison Limestone aquifer, we can expect the Madison Limestone aquifer to follow short- and long-term patterns in mountain precipitation that result from future climate change. However, if changes in climate and/or future development result in higher demand and higher capacity withdrawals, we may begin to see long-term declines, regardless of precipitation patterns.

Irrigation-supported alluvial aquifers will likely be resilient to climate change

Alluvial aquifers recharged by irrigation are expected to be resistant to climate impacts. More than 7000 miles (11,300 km) of irrigation canals lace Montana's river valleys and alluvial terraces. These canals, which are mostly unlined, carry about 10.5 million acre-feet (1.3x1010 m^3) of surface water each year to irrigate about 2 million acres (0.8 million ha).

In these valleys, losses from irrigation canals and seepage from irrigated fields constitute a significant fraction of aquifer recharge. Groundwater levels in such areas typically start rising during April and May when irrigation begins, remain elevated from midsummer to the end of the irrigation season, and then decline to an annual minimum just before the next growing season. This response is observed throughout the irrigated valleys in Montana.

Hydrographs from two Bitterroot Valley wells from the same aquifer demonstrate this behavior, and thus highlight the significance of irrigation recharge and the resilience of irrigation-supported aquifers to climate variability (Figure 3-20):

- A well from an irrigated area near Hamilton shows that groundwater levels rise quickly at the onset of irrigation, remain elevated throughout the irrigation season, and then decline in the late summer or fall when irrigation ceases.

- A well distant from irrigation near Florence shows a far different water-level response, which is synchronized with interannual and seasonal variation in Bitterroot River flow. Here, water levels peak close to when streamflow peaks, and then gradually fall back to a base level.

On average, the annual water-level fluctuation in the Hamilton well is nearly 10 ft versus 2 ft (3 m versus 0.6 m) for the Florence well. The timing and the magnitude of the seasonal fluctuations in the Hamilton well are consistent from year to year. This consistency demonstrates that interannual climate variability does not affect groundwater recharge or storage in this irrigated area. However, future improvements to irrigation infrastructure aimed at increasing the efficiency of water delivery are likely to greatly impact the extent of incidental recharge related to irrigation. Such changes will make alluvial aquifers such as that near Hamilton less resistant to climate change influence, in turn affecting groundwater contributions to streamflow in affected areas.

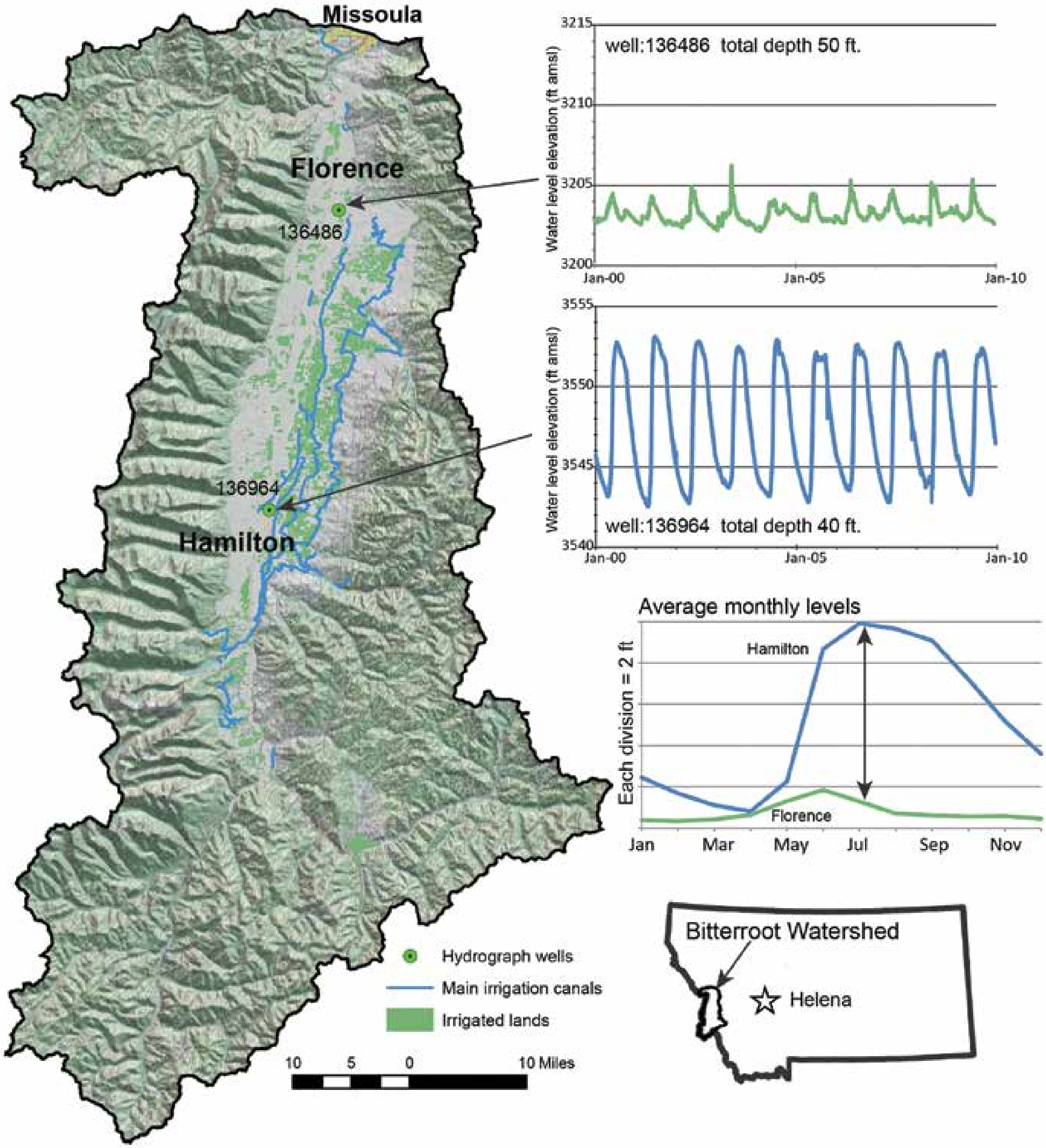


Figure 3-20. Hydrographs for two wells completed in the same aquifer near the Bitterroot River show very different responses. The well near Hamilton is downgradient from several irrigation canals and irrigated fields; the well near Florence is not located near irrigation. The average monthly water levels show the difference in seasonal response of groundwater levels and highlight the importance of irrigation water as a source of recharge to the shallow aquifers (MBMGb undated).

Fox Hills–Hell Creek aquifer, impacted by user withdrawals

Groundwater depletion occurs when the rate of groundwater recharge is less than the rate of discharge. The Fox Hills–Hell Creek aquifer underlies most of the eastern third of Montana and receives recharge from relatively narrow surficial exposures. Although the aquifer can be as much as 2000 ft (600 m) below the land surface, it provides water for domestic and livestock watering purposes, as well as municipal water for the towns of Baker, Circle, Lambert, and Richey.

In the lower Yellowstone River basin, the Fox Hills–Hell Creek aquifer serves about 1500 wells (Figure 3-21). The widespread use of the aquifer has resulted in persistent water-level declines, especially in the Yellowstone River valley. The hydrograph from observation well 1846 near Terry shows declining water levels of about 25 ft (7.6 m) during the past 33 yr (inset of Figure 3-21). The groundwater hydrograph shows no response to local climate variability and suggests that water use currently overwhelms or masks any variability related to climate. Projected shifts in temperature and precipitation are likely to reduce diffuse recharge to the Fox Hills–Hell Creek aquifer and accelerate the current depletion by water users. Increased demand on the aquifer will also occur with a warmer climate.

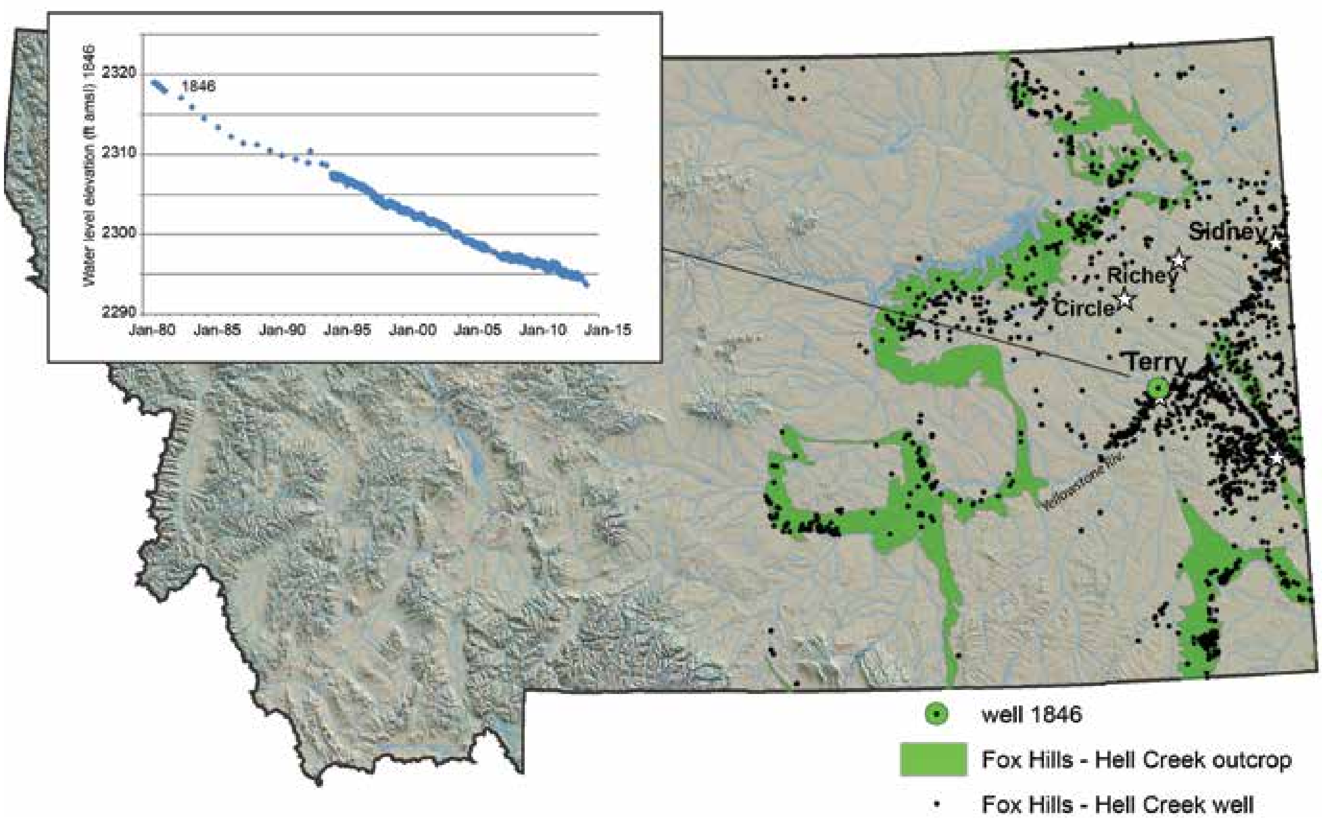


Figure 3-21. Water levels in the Fox Hills–Hell Creek aquifer near Terry are declining at a rate of about 1 ft/yr (0.3 m/yr) (MBMGb undated).

Groundwater systems are characterized by high storage capacity relative to inflows and outflows (Alley 2016). This characteristic will allow groundwater storage to play a key role in dampening the impact of climate variability on water resources (Taylor et al. 2013). Two strategies employing groundwater storage are:

- Coordinated use of groundwater and surface water resources.—Often referred to as "conjunctive use", this approach stresses usage of surface water during wet periods and stored groundwater during dry periods to best maximize water availability.
- Managed or artificial groundwater recharge with excess surface water.—The use of aquifers as natural storage reservoirs for later withdrawal helps avoid evaporative loss, ecosystem impacts, and other problems associated with large, surface-water reservoirs.

Both strategies require comprehensive hydrogeologic analysis due to the uncertainty and variability of the climate and sub-surface conditions.

The demand for groundwater is likely to increase in the face of projected climate variability and change (Brown et al. 2013) (see Climate chapter). Whether groundwater will be utilized to help meet future water demand will depend not only on the physical availability of groundwater, but also on its legal availability. Surface water and groundwater are managed as a single resource in Montana and both are subject to restriction based on the water rights doctrine of prior appropriation.

Effective management responses require information, including:

- specific knowledge of the hydrogeology for many aquifers across the state to assess the impact of climate change on groundwater resources and develop adaptive strategies; and
- long-term monitoring of groundwater levels, groundwater use, and surface-water flow to establish baseline properties and conditions for predicting change.

DROUGHT

Key Messages

Multi-year and decadal-scale droughts have been, and will continue to be, a natural feature of Montana's climate [high agreement, robust evidence]; *rising temperatures will likely exacerbate drought when and where it occurs.* [high agreement, medium evidence]

Changes in snowpack and runoff timing will likely increase the frequency and duration of drought during late summer and early fall. [high agreement, medium evidence]

Drought is a recurrent climate feature that occurs throughout the world, although it varies substantially from region to region. Drought can have broad and potentially devastating economic and environmental impacts (Wilhite 2000); thus, it is a topic of ongoing, statewide concern.

Through time, Montana's people, agriculture, and industry, like its ecosystems, have evolved with drought. Today, many entities across the state address drought, including private and non-profit organizations, state and federal agencies, and landowners, as well as unique watershed partnerships. These groups incorporate drought preparedness and management goals into Montana water policy (see Building Drought Resilience sidebar).

Drought is a complex phenomenon, driven by both climate and human-related factors. Although a clear definition of drought is elusive, most definitions fall into four interrelated categories:

- meteorological drought, defined as a deficit in precipitation and above average evapotranspiration that lead to increased aridity;
- hydrological drought, characterized by reduced water levels in streams, lakes, and aquifers following prolonged periods of meteorological drought;
- ecological drought, defined as a prolonged period over which an ecosystem's demand for water exceeds the supply (the resulting water deficit, or shortage, creates multiple stresses within and across ecosystems);[21] and
- agricultural drought, commonly understood as a deficit in soil moisture and water supply that lead to decreased productivity (in this assessment, we will treat this form of drought as an important component of ecological drought).

Here, we focus on hydrological drought, in keeping with the emphasis on water availability and streamflow.

Drought is also discussed in terms of its duration. This section will address both *persistent* drought, which we define as multiple years of below-average streamflow (within which individual seasons of above-average flow may occur); and seasonal drought, defined as below-average streamflow lasting months. In Montana, *seasonal* drought is most common and of greatest concern during the warm growing season in summer and early fall. We therefore refer to this as *warm-season* drought.

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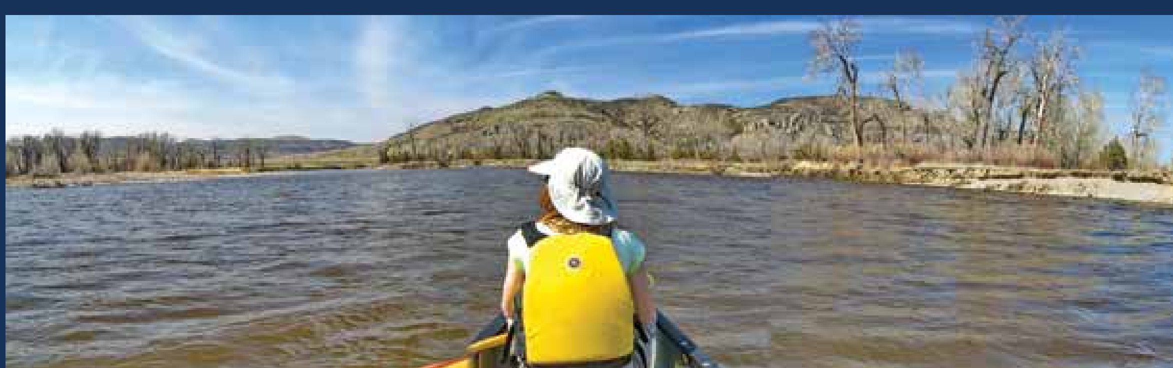
[21] *Ecological drought* has also been defined recently by a Science for Nature and People Partnership working group. Their definition is a prolonged and widespread deficit in naturally available water supplies that creates multiple stresses across ecosystems (Science for Nature and People Partnership undated).

Building Drought Resilience in Montana

In the past, Montana often addressed drought and flooding as temporary emergencies, with reactionary responses to an immediate crisis. Over the past decade, western water planners have learned that the best time to prepare for the impacts of drought or flooding is before those events occur. Thus, they have developed plans advocating a proactive hazard management approach.

Today, Montana's drought planning efforts take this approach, seeking to apply foresight, commitment, technology, and cooperation to diminish the impacts of drought. For example, water managers and users now employ improved short-term drought forecasting methods to better plan for and mitigate drought impacts. Even so, our forecasting abilities must further improve for Montanans to better prepare for short-term variation in weather patterns and expected long-term impacts associated with climate change.



Canoeing the Jefferson River. Photograph courtesy of Scott Bischke.

National Drought Resilience Partnership Montana Demonstration Project

Through the Montana Demonstration Project partners, Montana is forging new ground in bringing together agencies, resource managers, and communities to plan for drought impacts and build drought resilience within watershed communities. Teaming with the National Drought Resilience Partnership—a collaborative of federal and state agencies, watershed stakeholders, and non-governmental organizations—the Montana group is working to leverage and deliver technical, human, and financial resources to help address drought in the arid West.

The team selected the Missouri Headwaters Basin in southwest Montana for a national demonstration project. This basin experiences frequent drought, plays an important role in landscape connectivity in the Northern Rockies, and faces rapidly changing population and land use. The Montana Demonstration Project partners are working collaboratively to engage and train community-based drought coordinators to lead planning, mitigation, and project implementation in each of the eight watersheds in the basin. The individual watershed planning efforts will provide the basis for a scaled-up, integrated Headwaters Basin plan.

This unique partnership is successfully demonstrating a) the value of enhanced coordination, and b) how to effectively leverage federal, state, and private resources to build community and ecosystem resilience to prepare and adapt to a changing climate.

Text contributed by Ann Schwend, MT DNRC.

Persistent drought

During the past century, Montana experienced significant periods of persistent drought in 1917-1919, the late 1920s to early 1940s (the Dust Bowl droughts), the 1950s, the late 1980s to early 1990s, and the early 2000s (Figure 3-13). Most consider the Dust Bowl drought to be the worst multi-year drought in the observational record in Montana.

While these major droughtss affected all of Montana—and indeed much of the West—the severity, duration, and timing of each drought varied across the state (Figure 3-13), including in their influence on the larger river basins (MT DNRC 2015). In the 1950s, for example, rivers east of the Continental Divide show multiple years of below-average flow, while the Clark Fork at Saint Regis experienced above-average flows during the entire decade.

Studies of tree-ring-based reconstructions of drought, snowpack, and streamflow offer important insights about the long-term history of drought, as well as the natural variability of climate over the last millennium (Jackson et al. 2009). Reconstructions of snowpack, streamflow, and drought indices show that wet and dry periods, persisting between 10-25 yr, occurred throughout the western US (Cook et al. 2004; Pederson et al. 2006; Pederson et al. 2011b). Further, tree-ring reconstructions of drought (using the Palmer Drought Severity Index) show that a) the frequency and duration of droughts in the West were greater prior to 1200 AD than during the 20th century, and b) the past 300 yr have been wet relative to the long-term average (Cook et al. 2004; Cook et al. 2010).

Regional and local factors that influence persistent drought

A complex interplay of climate, hydrologic and ecosystem processes, and human impacts influences drought. For this assessment, we focus on the first two. However, it is notable that humans significantly impact streamflow and water supply, and, hence, patterns of drought. Those impacts must be included in future efforts to assess drought risk, manage water use and supply, and build resilience to climate change.

Natural variability in precipitation and temperature will continue to characterize Montana's climate in the future, resulting in droughts of varying duration and intensity. Within the context of this natural variability, human-driven changes in temperature and precipitation will affect future patterns of drought in Montana. For this assessment, we focus on important factors, described below, that affect the natural variability of persistent drought in Montana, as well as potential shifts in drought occurrence as a result of a changing climate.

- Precipitation.—Interannual variability in precipitation is widely accepted as the primary climate factor driving drought. While annual precipitation is expected to increase in many parts of Montana, precipitation projections are less certain than changes in temperature, making accurate assessment of future drought risk based on those projections difficult (Cook et al. 2014). Additionally, the total volume of annual precipitation is only a single factor that helps to predict drought; the frequency, intensity, character, and seasonality of precipitation are equally important (Sheffield and Wood 2008). For example, shifts from snow to rain in headwater areas and potential decreases in summer precipitation could have negative consequences for water supply in the seasons of highest water demand (see snowpack, snowmelt and runoff, and seasonal drought sections).

- Temperature.—Temperature variability can also affect drought, although its influence is much smaller than that of precipitation (Dai 2011; Livneh and Hoerling 2016). Historically, temperature appears to be a secondary response to drought, rather than an initial driver. In the prolonged absence of precipitation, soils dry out and the fraction of energy that once went into evaporation heats the land surface and forces temperatures higher (Lukas et al. 2014). In severe circumstances, a positive feedback then occurs, with high temperatures further exacerbating the drought. Several recent studies suggest that, while precipitation remains the primary driver of drought, the influence of high temperatures on drought is increasing, as shown for recent droughts in California and the Great Plains (Hoerling et al. 2014; Wang et al. 2014; Livneh and Hoerling 2016).

- Evapotranspiration and drought.—Rising temperatures cause increased rates of evaporation and plant transpiration, which together are referred to as evapotranspiration. This increased evapotranspiration will be one of the most significant influences on drought resulting from rising temperatures. In the absence of increased precipitation, higher rates of evapotranspiration can move substantial amounts of water back to the atmosphere (Figure 3-1), leading to reductions in streamflow, soil moisture, and groundwater recharge. Recent studies suggest a) a global trend toward drying of land surfaces since the 1980s (Sheffield and Wood 2008; Dai 2011; Dai 2013), and b) an increase in water deficits in the Northern Hemisphere since 2000 (McCabe and Wolock 2015), both resulting from rising temperatures and elevated levels of evapotranspiration. However, regional changes in evapotranspiration are less certain than global trends (Cook et al. 2014). Additionally, quantifying the effects of climate change on evapotranspiration—and subsequently to the water balance—is complex; so much so that future projections of drought risk vary significantly (Zwiers et al. 2013; Sheffield et al. 2012) depending on assumptions made about how evapotranspiration will respond to climate change. Among other factors, complexity results from uncertainty in how plants will respond to elevated greenhouse gases and changes in water availability, as shown below.

- Evapotranspiration is expected to increase with warming and, yet, plants can respond to elevated atmospheric CO_2 (that occurs in parallel with warming) by using water more efficiently leading to less water loss through evapotranspiration (Tesemma et al. 2015; Swann et al. 2016).

- Evapotranspiration is limited by water supply and, thus, long-term or seasonal increases in aridity will constrain potential increases in evapotranspiration caused by rising temperatures (Huntington and Niswonger 2012; Trenberth et al. 2014).

Surface water stored in reservoirs provides important warm-season water supplies in much of Montana, particularly in central and eastern areas that receive the lowest levels of average annual precipitation. A significant percentage of this stored water is currently lost to evaporation. For example, 7% of the water budget for the lower Missouri River Basin evaporates annually from Fort Peck Reservoir (MT DNRC 2014a). Additionally, in the many arid parts of Montana, runoff efficiency—the proportion of precipitation converted to streamflow—is already low (e.g., 4% of precipitation in the Musselshell leaves the basin as streamflow [MT DNRC 2014a]). Higher rates of reservoir evaporation due to rising temperatures could exacerbate both problems, resulting in reduced water supply and decreased ability for reservoirs to buffer summer periods of low streamflow.

Drought and the dominant role of sea-surface temperatures

As discussed in the Climate chapter, large-scale atmospheric circulation patterns connected to changes in sea-surface temperatures strongly influence natural variations in precipitation and temperature (e.g., Cayan et al. 1999; Mantua and Hare 2002). Shifts in sea-surface temperatures in both the Pacific and Atlantic oceans can produce conditions that lead to periods of drought (McCabe et al. 2004, Seager and Hoerling 2014).

A deeper understanding of these circulation patterns is required to predict persistent drought in Montana and the West accurately (Cook et al. 2007; Trenberth et al. 2014). The relationship between changes in sea-surface temperature and drought is complicated by many factors, including a) the large number of meteorological or other environmental phenomena involved; b) the widely varying timescales and large distances those phenomena act over; and c) the fact that those phenomena can amplify or dampen each other's effect on weather and climate (Schubert et al. 2016). Indeed, our current understanding of how sea-surface temperatures respond to climate change is relatively weak (see Climate chapter), severely limiting our ability to forecast persistent drought (Dai 2011; Seager and Hoerling 2014; Trenberth et al. 2014).

Likelihood of persistent drought

Given the known occurrence of long-term drought in Montana over the observed historical and paleo-climate records, there is very high likelihood that persistent drought will continue to be part of Montana's future climate, regardless of the effects of climate change.

There is relatively little consensus about how climate change will affect the incidence of persistent drought at global and regional scales, in large part due to the uncertainties discussed above. In addition, exclusion of human-related impacts such as irrigation, land use, and water diversion from most current climate models makes reliable projection of drought even less certain (Sheffield and Wood 2008). Across the western US, there is considerable variation in projected future drought risk, both regionally and among climate models.

Projections for the northern Rocky Mountains and northern Great Plains, including precipitation only, suggest that long-term droughts will not increase in frequency (Strzepek et al. 2010). However, projections for these regions that incorporate other changes in climate (such as temperature and evapotranspiration) predict increasing drought frequency in the latter half of the 21st century (Strzepek et al. 2010; Dai 2011; Cook et al. 2014), suggesting an increasing influence of temperature on drought. Amidst debates over changes in drought frequency, there is widespread agreement that rising temperatures will exacerbate drought when and where it occurs, leading to more rapid onset of drought and increased intensity (Strzepek et al. 2010; Peterson et al. 2013; Lukas et al. 2014; Trenberth et al. 2014). Such effects may already be occurring in some areas (Lukas et al. 2014).

In addition, strong evidence exists that climate change is likely to impact the occurrence and severity of warm-season drought (Cook et al. 2004; Sheffield and Wood 2008; Pederson et al. 2011a; Dai 2013; Trenberth et al. 2014).

Warm-season drought

Drought during the warm season is a common phenomenon in arid and snowmelt-dominated regions in the West, including much of Montana. In these areas, the majority of precipitation arrives as snow in winter and melts in spring to produce high streamflow that generally diminishes through summer. Even for areas in eastern Montana that receive most of their annual precipitation in spring and summer, water in larger watersheds is predominantly derived from mountain snowpack (MT DNRC 2014b), and thus streamflow there follows a similar seasonal pattern (Figure 3-6).

Warm-season drought can occur during years of persistent drought as well as years of average precipitation if, for example, high spring temperatures rapidly reduce snowpack. Changes in late-summer flows are likely to be more critical to people than changes in annual flows because the demand for water is highest in summer. Thus, understanding current trends and potential changes in warm- season drought is essential for building water resource resilience in Montana.

Observed trends in warm-season drought

Evidence for declining summer flows across much of the West comes from large-scale studies in the Sierra Nevada; the Columbia, Colorado (Das et al. 2011), and Upper Missouri basins (Norton et al. 2014); and many small watersheds in western Montana, Idaho, Alberta, and British Columbia (Rood et al. 2008; Leppi et al. 2012). Widespread declines in August streamflow and increased frequency of low flows have been reported in both pristine and regulated watersheds of western Montana, Idaho, and Wyoming, with the most pronounced trends in pristine sites (Leppi et al 2012).

Most studies link declining summer flows with increased winter and spring temperatures, reduced snow accumulation (see snowpack section), and earlier snowmelt and spring runoff (see snowmelt and runoff section) (Rood et al. 2008; Kim and Jain 2010; Leppi et al. 2012). The problems of declining summer flows are compounded in watersheds with significant water use.

Factors associated with low summer flows in Montana

Here, we investigate factors associated with summer low flows in our focal rivers by examining correlations between historical (1929-2015) climate and August streamflow (e.g., the relationship between winter or spring precipitation and August flow; Figure 3-22). While this investigation cannot be used to *predict* August streamflow in the future, it can help reveal patterns of seasonal temperature and precipitation that tend to produce higher or lower summer flows. It should be acknowledged, however, that increased water use during the summer makes it harder to explicitly separate the effects of climate from water use.

Factors that determine August flows vary across the state.—In our focal watersheds, we find that for rivers fed primarily by mid- to high-elevation snowmelt (e.g., the Yellowstone at Billings, the Clark Fork at Saint Regis, and the Missouri at Toston), August flows have a strong positive relationship with winter (November-March) precipitation and a strong negative relationship with spring (April-June) temperatures. Thus, we can expect that years with low winter precipitation and high spring temperatures will lead to low August flows. In addition, for the Yellowstone at Billings, when recent years (1980-2015) are compared to the entire period of record (1929-2015), the relationship between high spring temperatures and low August flows (not pictured in Figure 3-22) is strengthened, a finding consistent with literature suggesting that recent warming is exacerbating low summer flows (Hay et al. 2011; Leppi et al. 2012; Huntington and Niswonger 2012).

Although these three rivers receive the vast majority of their annual precipitation in winter and spring (70-78%), summer precipitation can also have an important influence on August flows (Figure 3-22). For the Marias River near Shelby and the

Relative Influence of Increasing Temperature and/or Precipitation on August Streamflow (*=no significant influence)

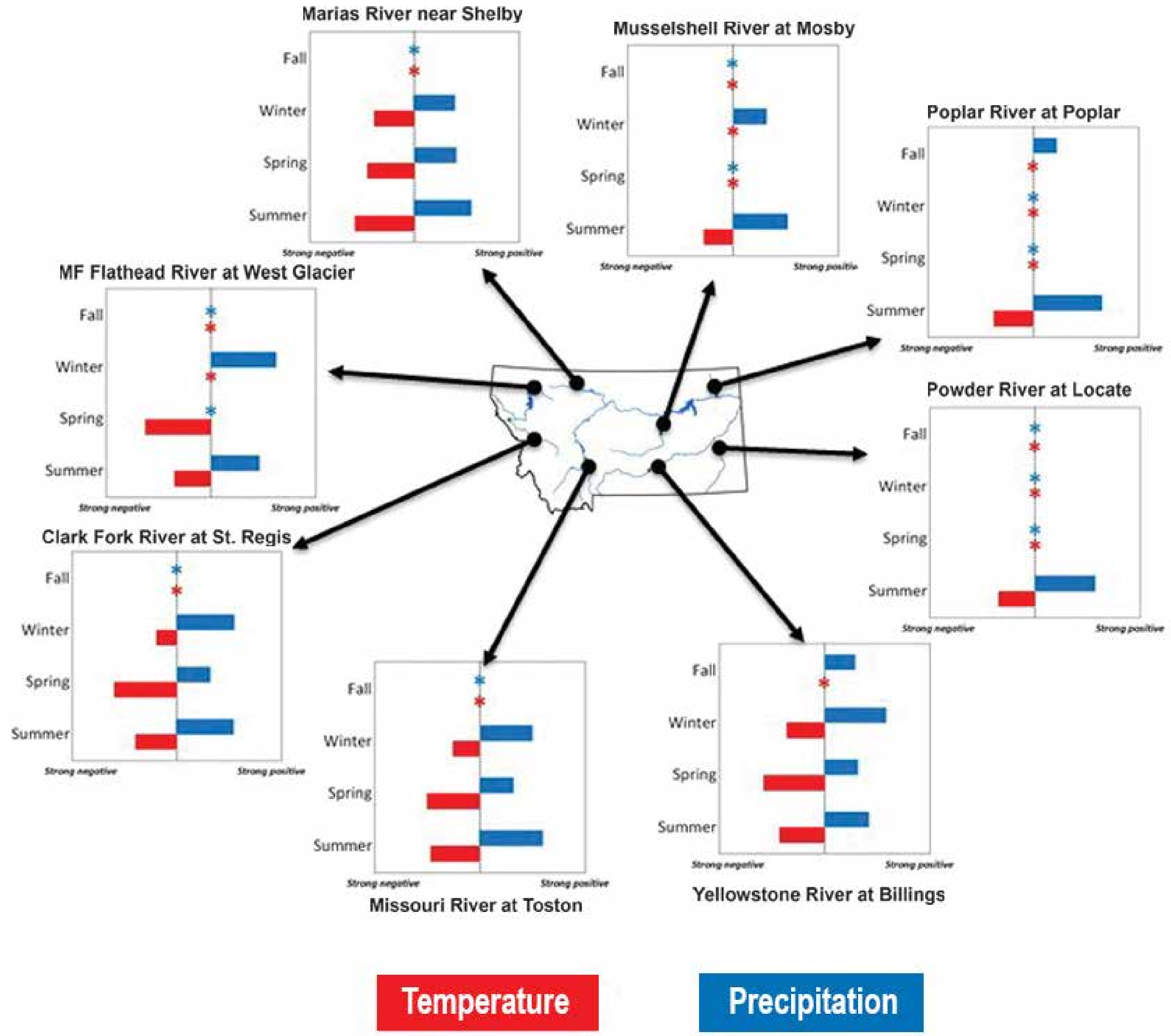


Figure 3-22. Relative influence of temperature and precipitation on August flows for the focal rivers of this assessment. In general, warmer temperatures have a negative influence on August streamflow, while precipitation has a positive influence on flows. Differences exist among seasons and rivers.

Musselshell River at Mosby, August flows are lowest during years of high summer temperatures (Figure 3-22) and low summer precipitation. For the Marias River near Shelby, high spring temperatures also negatively influence August flows, likely because of accelerated snowmelt.

For the two focal rivers in eastern Montana (Powder River near Locate and Poplar River near Poplar), August flows are most dependent upon summer precipitation (Figure 3-22), likely because eastern Montana receives a higher percentage of precipitation in spring and summer relative to the other parts of the state.

Climate projections and warm-season drought.—Future changes in climate are likely to increase the incidence of warm-season drought (Cook et al. 2004; Sheffield and Wood 2008; Pederson et al. 2011a). Based on the relationships between climate and August flows described above, projected warming in winter and spring will likely lead to lower summer flows and/or low flows of longer duration. High warm-season temperatures show a negative relationship with August flows in several watersheds, an effect that is likely to be magnified with rising summer temperatures and the projected increase in number of days over 90°F (32°C) (see Climate chapter).

Any potential decline in summer precipitation is also projected with medium confidence for many areas in Montana (see Climate chapter). Small decreases in summer precipitation could exacerbate the occurrence and severity of warm-season drought because a) many smaller watersheds in eastern Montana are fed more by spring and summer precipitation than by winter snowpack (MT DNRC 2014b), and b) low August flows show a strong correlation with summer precipitation in all focal watersheds.

Projected hydrographs for our focal watersheds demonstrate reductions in late-summer flows for all rivers except the Musselshell, although variation in the magnitude of change and projection confidence exists (see Figure 3-12). These projections, therefore, generally illustrate that a higher proportion of the annual flow will leave Montana watersheds earlier in the year, resulting in lower flows during the summer months. Lower flows are a concern for multiple reasons, as described below.

- Although Montana has experienced a long history of warm-season drought, projected changes in temperature and precipitation could have a substantial impact on the severity of warm-season drought in the future.

- Short-term drought during the season of highest demand can a) test water supply infrastructure, and b) have severe consequences for human and natural systems (Luce and Holden 2009).

- Given the projected increases in streamflow during winter and spring, maintaining streamflows during warm season months will likely necessitate reconsideration of water storage practices and reservoir management.

- Changing seasonality of water availability will likely put additional stress on the rigid and legally encumbered water rights system, making it difficult to access water at critical times (Udall 2013).

- Changes in stream temperature due to lower flows and rising air temperature are likely to have catastrophic impacts on some aquatic species, with ripple effects on Montana's important river-based recreation industry (see Warming Rivers and Streams sidebar).

Warming Rivers and Streams

*Montana's 40,000 miles (64,000 km) of perennial rivers and streams support world-famous trout fisheries. They also provide habitat for rare and temperature-sensitive species like bull trout (*Salvelinus confluentus*), cutthroat trout (*Oncorhynchus clarkii*), and pearlshell mussels (*Margaritifera margaritifera*).*

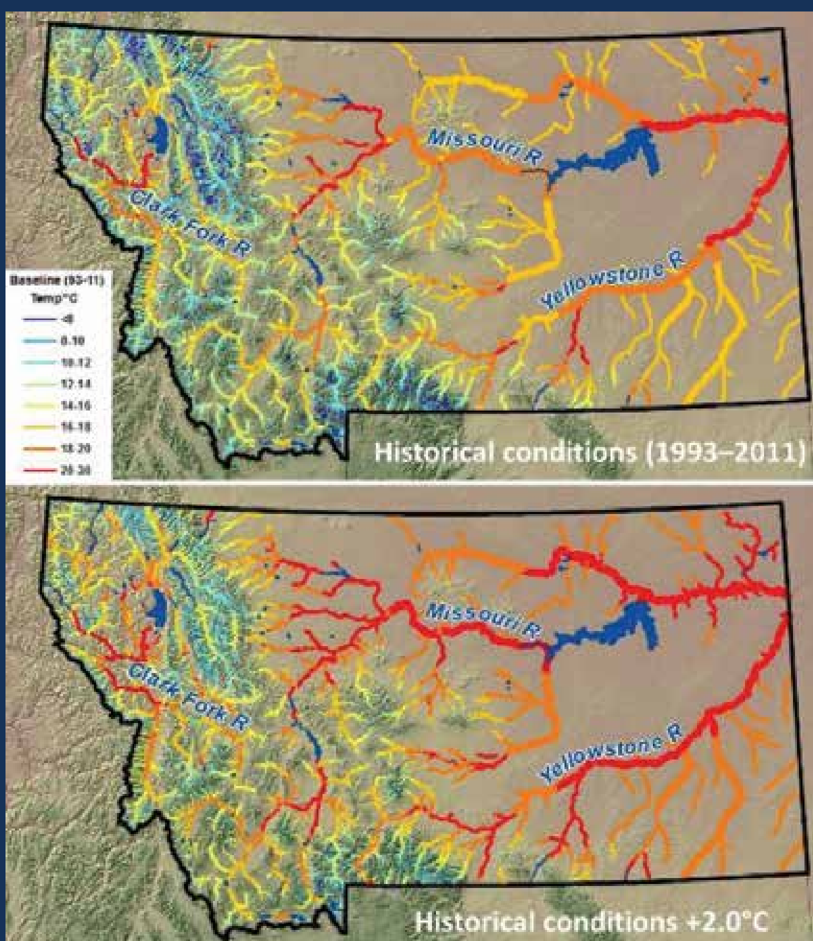
Researchers have recently developed high-resolution stream climate maps (Isaak et al. 2016) based on extensive stream temperature data collected by several agencies across the state. The maps show that summer stream temperatures vary considerably throughout the state. Those temperatures generally reflect patterns in average air temperatures—usually being coldest in the high mountains and warmest at low elevations and in the eastern plains.

Changes in climate described in this assessment, especially declining summer flows (Rood et al. 2008; Leppi et al. 2012) and increasing air temperatures (Pederson et al. 2010), have caused temperatures to increase in the state's rivers and streams at the rate of 0.18-0.36°F (0.1-0.2°C/decade) (Isaak et al. 2012). Stream warming rates are slower than air temperature warming rates due to the buffering effects of groundwater, but any temperature increase can be important for cold-blooded aquatic species. Two ramifications of increasing stream temperatures follow.

- *Fish moving upstream.—Studies already show that distributions of brown trout (*Salmo trutta*) and bull trout have shifted upstream as fish seek to access cooler habitats (Eby et al. 2014; Al-Chokhachy et al. 2016). In addition, warm-water fishes (e.g., smallmouth bass [*Micropterus dolomieu*]) have been caught with increasing frequency in historically cold sections of some rivers, such as the Yellowstone River near Livingston. Cold headwater streams are poised to provide important climate refuge for species requiring cold waters (Isaak et al. 2015).*

- *Possible changes in Montana fishing regulations.—In larger rivers at lower elevations, warming trends may result in more frequent fishing season closures and disease outbreaks, such as the mountain whitefish (*Prosopium williamsoni*) kill on the Yellowstone River in the fall of 2016 (MFWP 2016, Wright 2016). Some sections of rivers that currently support trout fisheries may transition gradually into bass fisheries.*

It is difficult to know precisely how much warmer Montana's rivers and streams will become in this century, but across the state water temperatures will likely follow rising air temperatures.



Climate map showing average summer temperatures in Montana's rivers and streams during historical baseline period of 1993–2011 (top panel) and a late-century scenario in which temperatures are warmer than historical conditions by 3.6°F (2.0°C; bottom panel). River segments colored red are usually too warm for popular cold-water species like trout. A more detailed version of this map, as well as the stream temperature data used in it, are available from the NorWeST website (USFS-RMRS undated). Sidebar text and figure contributed by Daniel J. Isaak, US Forest Service, Rocky Mountain Research Station.

Flooding.—While drought likely represents the greatest persistent water-resource concern in Montana, flooding has also occurred regularly throughout the state's history, resulting in loss of life and substantial damage to property, infrastructure, and riparian ecosystems. Flash flooding events typically occur with little warning, are difficult to predict, and are caused by a variety of climate and human-related factors. The geographical extent of flooding is often more limited than that of drought; flood history in Montana therefore varies significantly by watershed and basin (Table 3-3).

In Montana, flood events can occur at any time of the year, but the causes of flooding vary among seasons. Most spring floods are caused by rapid snowmelt, particularly during rain-on-snow events in which rain infiltrates and degrades the existing snowpack. The most severe and destructive floods in the state's observational record have resulted from rain-on-snow events (Table 3-3) (Paulson et al. 1991; MT DNRC 2015) that occurred after a period of relatively cold weather. During these events, frozen soils prevent the infiltration of surface water into soils, resulting in greatly elevated runoff (MT DNRC 2015). In northwestern Montana, rain-on-snow events are one of the most frequent causes of annual maximum streamflows (MacDonald and Hoffman 1995; Ferguson 2000).

Natural variability in precipitation also plays a significant role in flooding in Montana, sometimes in combination with rain-on-snow events. For example, in the huge flood of June 1964, 13 inches (33 cm) of rain fell in 24 h near Augusta, Montana, nearing the average annual precipitation for the region in a single day. This record-breaking rainfall on a higher-than-average and late-melting snowpack along the Rocky Mountain Front caused the overtopping of the Gibson Dam on the Sun River, and the failure of Swift Dam on Birch Creek and Lower Two Medicine Dam on Two Medicine Creek. The flood caused extensive damage and resulted in 30 fatalities, all of which were on the Blackfeet Reservation.

Flood events can also occur in winter as a result of ice jams, which impede flow in the river channel and lead to floodplain inundation. These floods are most common east of the Continental Divide during persistent cold weather fronts. Interestingly, Montana has recorded more ice jam events than any other state in the continental US (US Army CRREL undated). Floods that occur during summers are generally caused by large convective rainstorms and are most common in the eastern plains, particularly in the lower Yellowstone River Basin.

Human factors play a significant role in modifying flood regimes. Activities, such as urbanization, forest clearing, wetland drainage, and stream channelization, tend to amplify flooding, while water management practices, such as reservoir storage operation, can often prevent or moderate the peak flows that lead to large floods (Kunkel at al. 2003; Rood et al. 2016). Consideration of these factors will be critical for preventing and mitigating floods into the future.

Table 3-3. Montana flood history from 1908-2011 from the National Water Summary and recent observations (Paulson et al. 1991).

Date	Area affected	Recurrence interval (yrs)	Description	Cause
June 1908	Clark Fork Basin, Missouri headwaters	Unknown	Widespread and severe; worst flood until 1964; lives lost, 6	Excessive spring rains and snowmelt runoff
Sept 1923	Powder River basin	Unknown	Largest known discharge at Moorhead.	Intense rain
May-June 1948	Clark Fork, Flathead, Kootenai basins	25 to 50	Severe	Intense rain and rapid snowmelt runoff
April 1952	Milk River basin	25 to >100	Severe on Milk River main stem	Rapid snowmelt runoff
May-Jun 1953	Missouri headwaters	25 to100	Moderate to severe	Intense rain and rapid snowmelt runoff
June 1964	Missouri headwaters (Sun, Teton, Marias), Clark Fork basin	50 to >100	Worst on record; lives lost, 30 (all on the Blackfeet Reservation)	Intense rain and rapid snowmelt runoff
Jan 1974	Kootenai River basin	25 to >100	Severe on several Kootenai tributaries	Intense rain and rapid snowmelt runoff
May-July 1975	Missouri headwaters, Clark Fork basin	25 to 100	Severe in most areas affected in 1964	Intense rain and rapid snowmelt runoff
May 1978	Bighorn, Powder and Tongue basins	10 to >100	Severe on larger tributaries; lives lost, 1	Intense rain and rapid snowmelt runoff
May 1981	West-central Montana	10 to >100	Severe; centered on Helena	Intense rain and rapid snowmelt runoff
Sept 1986	Milk River basin	10 to >100	Severe on larger tributaries; lives lost, 1	Intense rain
June 1996	Statewide	50 to 100	Ice jam flooding (Feb) in the Clark Fork and Yellowstone basins and widespread spring flooding	Intense rain and rapid snowmelt runoff
June 1997	Statewide	50 to 100	Severe and widespread flooding impacting wide geographic area,	Record statewide snowpack, Intense rain and rapid snowmelt runoff
May-June 2011	Statewide	50 to >100	Largest flood of record for Missouri River near Wolf Point and Yellowstone River near Livingston. Flooding most severe on the Musselshell River.	Above average mountain snowpack, spring rainfall, and extensive and late melting prairie snowpack

Trends in flood-related precipitation.—

Determining trends in flood events and their underlying causes is difficult due to the complex interplay of climate and human-related factors. Many studies have therefore examined flood-related precipitation events instead (Karl and Knight 1998; Kunkel 2003; McCabe et al. 2007).

Studies have shown an increase in global and North American extreme precipitation events since 1970 (Karl and Knight 1998; Peterson et al. 2013; Rood et al. 2016). In the US, increases in extreme precipitation have been most substantial in the East, while trends in the West appear to be mixed and location specific (Salathé et al. 2014).

McCabe et al. (2007) analyzed the frequency of rain-on-snow events at over 400 sites in the western US between 1949 and 2003 and found declining trends at lower elevations and increasing trends at higher elevations. Reductions in rain-on-snow events at lower elevations are attributed to declines in the extent of low-elevation snowpack caused by warming (McCabe et al. 2007). Increases at higher elevations are likely due to a high-elevation snowpack that has been largely unaltered by warming (Mote et al. 2005), combined with increased variability of late-fall-winter precipitation.

The above studies and others (e.g., Hamlet and Lettenmeier 2007) suggest that change in flood risk during the latter half of the 20th century has been a function of both precipitation (increased variability) and temperature (warming in mid winter). Climate-driven changes in both of these variables will continue to affect flood risk in the future.

Future flood risk.—

Warming will continue to reduce mountain snowpack, and this could reduce flood risk related to rain-on-snow events by reducing the quantity of water available for release stored as snow (Cohen et al. 2015). Yet warming is also likely to increase the amount of winter and spring precipitation that falls as rain (particularly in rain-snow transition zones), which will accelerate snowmelt and could increase flood risk, depending on antecedent snowpack, soil moisture, and other conditions. As such, rising temperatures alone will influence flood risk, regardless of trends in precipitation (Salathé et al. 2014); yet the effects will likely be location- and event-specific and therefore difficult to predict (Cohen et al. 2015).

Future precipitation projections show a general increase in extreme events at a global scale (Min et al. 2011; Rood et al. 2016), and regional climate models also consistently predict increases in extreme precipitation in the northwestern US. In Montana, the frequency of wet events (days with more than 1 inch [2.5 cm] of rain) and variability in interannual precipitation are both projected to increase slightly by mid to late century (Figures 2-25 and 2-20).

There is considerable uncertainty surrounding future flood risk in response to climate change, and some research suggests that extreme precipitation events can actually intensify more quickly than what is projected by general circulation models (Min et al. 2011; also see section on GCMs in Climate chapter). Additionally, flood risk depends on specific storm characteristics that are difficult to capture in most models (Salathé et al. 2014). Moreover, the particular effects of projected changes in temperature and precipitation on flood risk will depend on location, elevation, and antecedent weather conditions, as well as human practices that impact flooding.

KEY KNOWLEDGE GAPS

- **Water demand and management in the context of a changing climate.**—Although the direct influences of climate change on water supply have received substantial attention (as evidenced by this assessment), much less is known about the intersection between changes in climate and water demand and/or water management. New solutions are needed that balance the multiple, and sometimes competing, demands for water in the context of changing or shifting water supplies (Poff et al. 2016). Communication and collaboration among multiple stakeholders, including universities, agencies, non-governmental organizations, and citizen groups, will be paramount. The regional basin water plans in Montana (e.g., MT DNRC 2014a-d) represent a bold and critical first step, but there is much work to be done.

- **Improving the accuracy of models in Montana.**—Many of the downscaled climate-hydrology projections are not yet calibrated for specific basins across Montana. Thus, when the models agree, we have relatively high confidence in the *direction* of projected changes, but much less confidence in the *magnitude* of future changes for specific river basins. The collaboration between MT DNRC and the Bureau of Reclamation (see sidebar) and other ongoing efforts associated with the Northwest Climate Science Center (Integrated scenarios project undated) are helping to close this gap, but additional modeling and local hydrologic expertise will be needed.

  In addition, we know that groundwater-surface water interactions are central for projecting climate change impacts on water resources, particularly in snowmelt-dominated watersheds. These interactions are not typically integrated in hydrologic models, but such efforts will be necessary for improving our projections about climate change and water supply (Huntington and Niswonger 2012).

- **Maintain and expand our water monitoring network.**—Our knowledge about current and future water supplies depends critically on our ability to monitor the water cycle across Montana and beyond. Our current network of weather stations, streamflow gages, groundwater wells, and snowpack monitoring sites must be maintained and expanded to better represent ongoing changes in the state. Current collaborations between USGS, Montana Bureau of Mines and Geology, and the Montana DNRC are helping to support this monitoring network, but additional investment in this area will serve as insurance for managing a sustainable water future.

CONCLUSIONS

Future changes in climate *will* alter Montana's hydrology. Although the specific magnitude of changes remains uncertain, two conclusions regarding the general character of changes can be made with high confidence:

- Rising temperatures will reduce accumulation of snowpack, shift historical patterns of streamflow in Montana, and likely result in additional stress on Montana's water supply, particularly during the summer and early fall.
- Rising temperatures will exacerbate persistent drought periods that are a natural part of Montana's climate.

The goal of this chapter has been to provide scientific data on the impacts of climate change on Montana's water supply, which are crucial to the health of Montana's agriculture, industry, municipalities, and human and natural ecosystems. Building resilience for the future will require:

- cooperation between legislators, planners, scientists, managers and water users across the state;
- a water use system that is flexible and able to adapt to changes in timing of water supply;
- a focus on other means for natural and artificial storage of water for use during times of high demand; and
- explicitly addressing the issue of water use and demand in conjunction with best data on climate and water supply

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Smoke over the Bitterroot Mountains.
Photograph courtesy of Philip Higuera.

KEY SECTOR

04. FORESTS AND CLIMATE CHANGE IN MONTANA

Alisa A. Wade, Ashley P. Ballantyne, Andrew J. Larson, and W. Matt Jolly

In this chapter, we interpret how past and projected shifts in climate—as described in the Climate chapter—may influence Montana forests. It is important to note that any potential effects will be spatially and temporally variable, depending on current forest conditions, local site characteristics, environmental influences, and annual and decadal patterns of climate variability, such as the El Niño-Southern Oscillation cycle, which can drive regional weather and climate conditions. Additionally, when discussing drought in this chapter, we are referring to ecological drought as defined in the Drought sidebar of the Climate chapter. The summary of potential climate influences on forest resources provided here are, in part, focused on assisting managers and policy makers develop management responses. Forest managers throughout Montana are key players in maintaining the health of our forests and, ultimately, forest managers will need to consider

KEY MESSAGES

- Increased temperatures will have positive or negative effects on individual trees and forest-wide processes, depending on local site and stand conditions, but impacts from increased extreme heat will be negative. *[high agreement, moderate evidence]*
- Direct effects of climate change on individual trees will be driven by temperature in energy-limited forests and moisture in water-limited forests. *[high agreement, moderate evidence]*
- The speed and magnitude of climate change may mean that increased forest mortality and contractions in forest distributions will outpace any gains in forest growth and productivity over the long run, leading to a net loss of forested area in Montana. *[medium agreement, limited evidence]*
- Direct effects of climate change on trees and forests, such as warmer, wetter conditions improving forest productivity or warmer, drier conditions increasing tree mortality, will be secondary to the impacts of altered forest disturbance regimes, such as changes in forest fire behavior and area burned. *[high agreement, limited evidence]*
- An increase in fire risk (i.e., probability of occurrence)—including an increase in size and possible frequency and/or severity (i.e., tree mortality)—is expected in the coming century as a result of a) prolonged fire seasons due to increased temperatures, and b) increased fuel loads from past fire suppression. *[high agreement, robust evidence]*
- Rising temperatures are likely to increase bark beetle survival *[high agreement, strong evidence]*, but climate-induced changes to other insects and forest pathogens are more varied and less certain. *[medium agreement, moderate evidence]*
- Forest responses to climate change may be non-linear and complex due to feedbacks. *[high agreement, limited evidence]*
- There may be a reduction in the amount of carbon stored in forests. *[low agreement, limited evidence]*

specific adaptation actions in response to current and potential climate changes. Forest managers also have an important role to play in climate change mitigation via efforts to increase forest carbon storage.

BACKGROUND

Forest ownership, communities, and distribution in Montana

In Brief

- *There are approximately 23 million acres (9.3 million ha) of forested land in Montana, with the majority publicly owned and in the western part of the state.*
- *The three most common forest types in the state are dominated by Montana's most commercially important species: Douglas-fir, lodgepole pine, and ponderosa pine.*
- *Forest conditions in Montana are varied, and potential impacts from climate change will overlay on existing stresses to forests.*

The Montana State Assessment of Forest Resources (MT DNRC 2010) estimates that forested land covers 23 million acres (9.3 million ha) in Montana (Figure 4-1). The majority of Montana forestlands occur in the northwestern climate division (approximately 50%), followed by the southwestern, central, and south central divisions. Additionally, the majority (16.3 million acres [6.6 million ha], 71%) is publicly owned, under the jurisdiction of federal and state agencies (Figure 4-2). Tribal ownership accounts for 5% (1.2 million acres [0.49 million ha]) of forests in Montana. Approximately 5.5 million acres (2.2 million ha) of forestland (24%) is privately owned, with the bulk (4.4 million acres [1.8 million ha], 19% state total) held by more than 83,000 nonindustrial private landowners, and the remainder managed by private industrial forest products companies.

Existing Land Cover in Montana

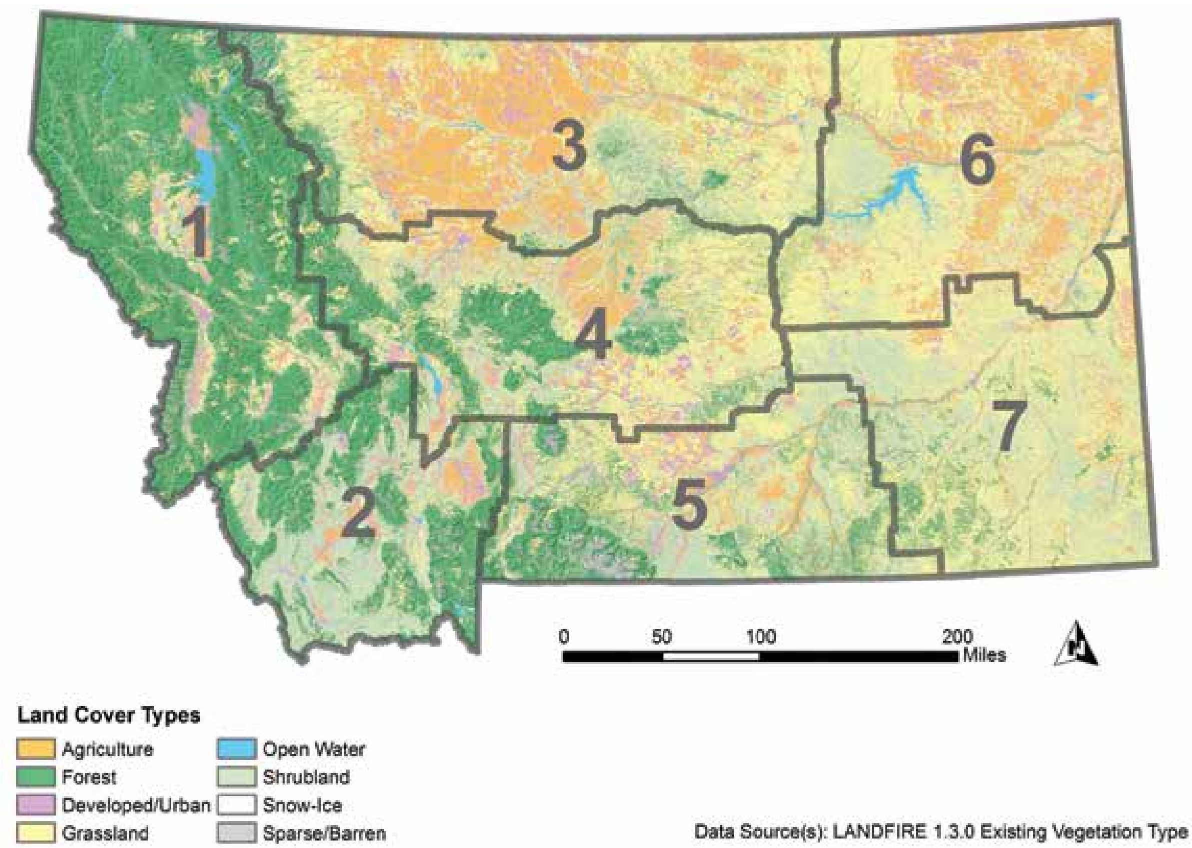


Figure 4-1. Existing land cover in Montana (Landfire 2012). Gray boundaries delineate climate divisions: 1-northwestern, 2-southwestern, 3-north central, 4-central, 5-south central, 6-northeastern, 7-southeastern (see Climate chapter).

There are 10 primary forest types—defined by the dominant tree species in a given area—in Montana as identified and quantified in the Montana State Assessment of Forest Resources (MT DNRC 2010). The three most widespread and commercially important tree species and their direct and indirect sensitivities to climate change are described below.

- Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) forests occur in cooler settings, but can tolerate a variety of climate conditions. They are found predominantly in the northwestern climate division (but also in the southwestern and central divisions), on approximately 7 million acres (2.8 million ha) in Montana (Figure 4-3). Douglas-fir trees are moderately tolerant of fire and tolerate drought better than many other species. Douglas-fir forests are subject to damage from western spruce budworm and Douglas-fir beetle, as well as several root diseases (e.g., Armillaria root disease).

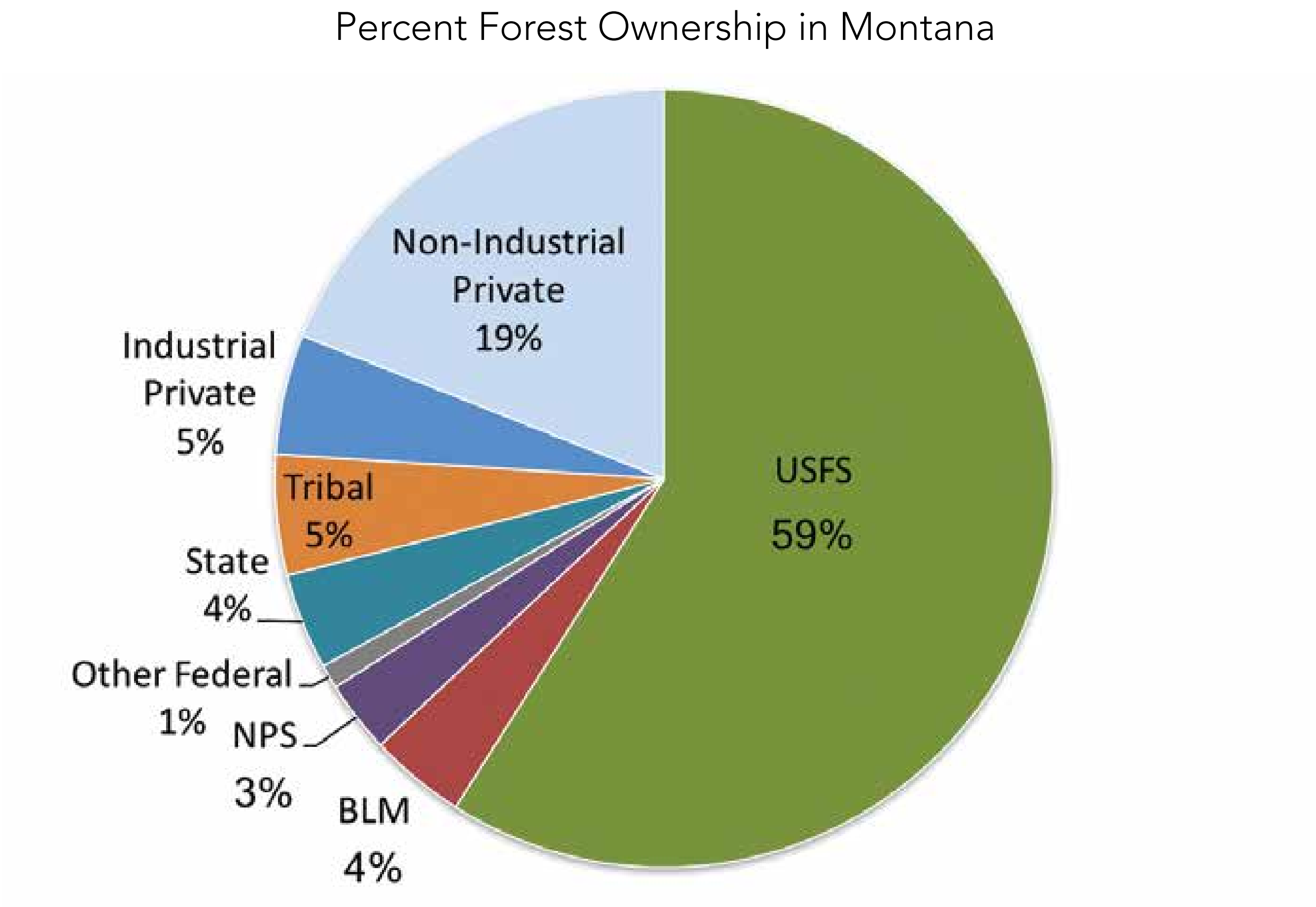


Figure 4-2. Percent forest ownership in Montana (adapted from MT DNRC 2010).

- Lodgepole pine (*Pinus contorta* var. *latifolia*) forests occupy approximately 4.9 million acres (2.0 million ha) in Montana (statewide, though primarily in the northwestern and southwestern climate divisions). Lodgepole pine trees grow on moist soils and are highly frost tolerant, but are less drought and fire resistant than Douglas-fir. Still, lodgepole pine forests are well adapted to recolonizing burned areas since lodgepole pine trees reach reproductive maturity at a young age. Lodgepole pine trees are susceptible to mountain pine beetle infestation and resulting mortality.
- Ponderosa pine (*Pinus ponderosa*) forests are found in drier areas of Montana, predominantly west of the Continental Divide, although east of the Continental Divide ponderosa pine is the dominant commercial timber species. Ponderosa pine forests occupy approximately 3 million acres (1.2 million ha) in Montana, primarily a) mixed with Douglas-fir trees in the northwestern, southwestern, and central climate divisions, and b) as a single species in the south central and southeastern climate divisions. Compared to many other conifers, ponderosa pine trees have deep

roots, making them more drought tolerant, and thick bark and high crown, making them more fire adapted. Like lodgepole pine, ponderosa pine trees are susceptible to mountain pine beetle infestation and resulting mortality.

Existing Forest Cover Type in Montana

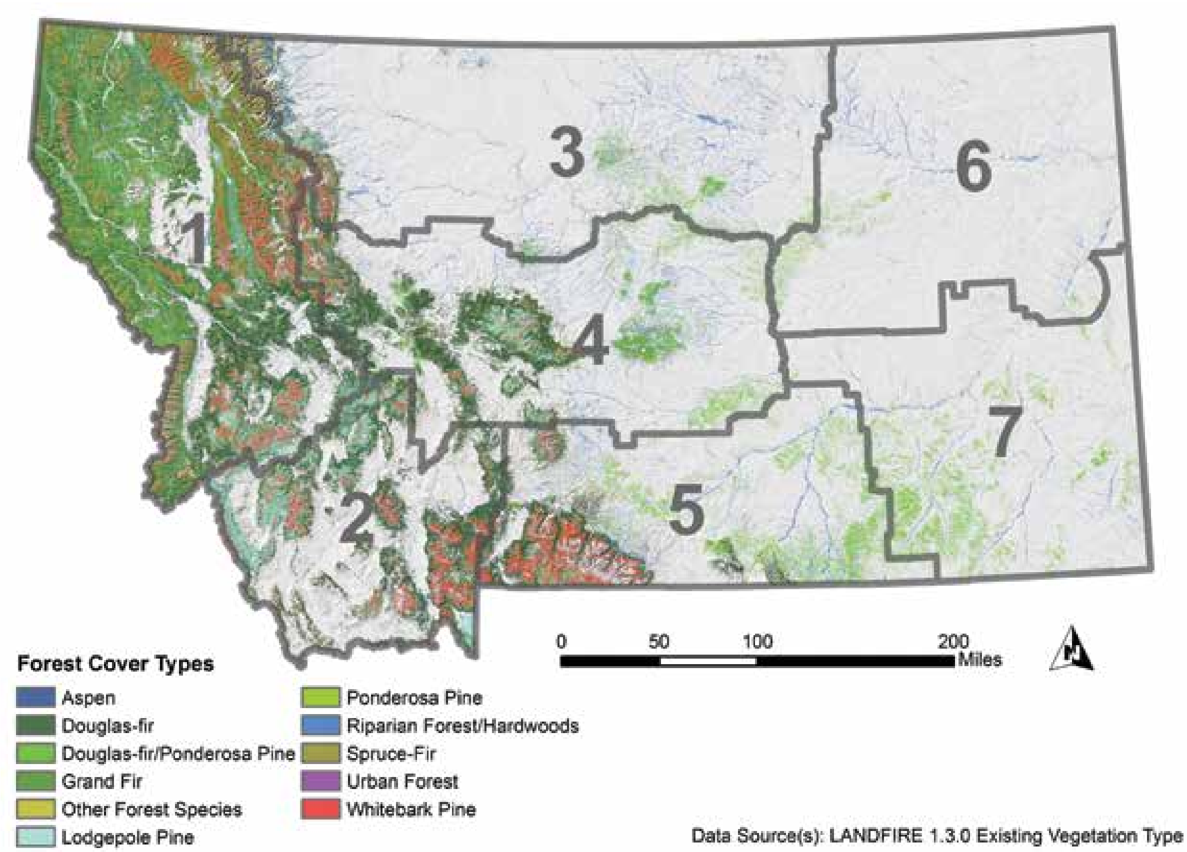


Figure 4-3. Existing forest cover type in Montana (Landfire 2012). Gray boundaries delineate climate divisions (see Figure 2-3).

Other conifer forest types found in Montana are spruce-fir forest (primarily composed of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), as well as forests dominated by western larch (*Larix occidentalis*), grand fir (*Abies grandis*), limber pine (*Pinus flexilis*), and miscellaneous western softwoods. An additional forest type is composed of hardwoods, including aspen (*Populus tremuloides*), cottonwood (*Populus trichocarpa* and *P. deltoides*), box elder (*Acer negundo*), bur oak (*Quercus macrocarpa*), green ash (*Fraxinus pennsylvanica*), willow (*Salix* spp.), and birch (*Betula papyrifera*). Of these hardwood species, cottonwood is the most abundant; it is concentrated in riparian areas of central and eastern Montana.

Urban forests also provide important benefits to quality of life in Montana. However, urban forests, which include many nonnative species, are not a focus of this chapter. Additionally, we will not focus on forest understory species (e.g., shrubs and grasses) despite their importance as wildlife habitat, livestock forage, fire fuels, and socio-cultural importance (see Socio-cultural sidebar). Both urban forests and the forest understory include a vast number of vegetation species, and consideration of species-by-species impacts is beyond the scope of this report.

Potential climate impacts to forests

In Brief

- *Forests have evolved, adapted, and transformed in response to natural processes, including disturbance and climate shifts, over the millennia.*
- *Current levels of atmospheric carbon dioxide are at their highest level in approximately 3 million years, and projected to increase, which will drive climate changes.*
- *Temperatures in Montana have increased and are projected to continue to rise; there has been no significant change in mean annual precipitation across Montana, but most models project an increase in mean annual precipitation with spring contributions greatest and with slightly reduced summer precipitation. The combination of rising summer temperatures, potential reductions in snowpack (see Water chapter), and decreased or similar summer precipitation will likely make droughts more severe when they do occur. The frequency and severity of extreme events (e.g., drought, extreme hot days) will be enhanced or diminished depending on annual and decadal climate oscillations.*
- *Individual tree species may prove to be more susceptible to projected changes in climate conditions and associated disturbances, but the actual response of individual species will be spatially complex and dependent on local factors like soils, aspect, water, and nutrient availability.*

- *There will be direct effects (related to increased temperatures and shifts in precipitation) and indirect effects (changes in disturbance regimes as a result of the direct effects) on forests from climate change.*

- *Shifts in temperature and precipitation can have both positive and negative direct effects on forest establishment and regeneration, growth and productivity, and mortality. Overall, net impacts are likely to be negative, particularly in water-limited areas.*

- *Indirect effects from climate change on forest disturbance regimes will likely have the greatest impacts on forest ecosystems, and will complicate patterns of direct effects. Key indirect effects from climate change are likely increases in fire and insect-caused mortality.*

- *Climate change will directly alter the range of forests with range expansion in some regions and range contractions in other regions. Indirect climate change impacts, such as drought or beetle-induced mortality, will also constrain forest ranges.*

- *Climate-driven impacts to forest ecosystems may be enhanced or reduced by changes in human land use or management at the forest-stand scale. Forest stand and local site conditions will also greatly influence patterns of climate-driven impacts.*

Change is the norm for forests, and over millennia Montana's forests have transformed and adapted as a result of variations in climate, disturbance, and other natural processes (Whitlock 1993; Brunelle et al. 2005; Power et al. 2011). However, current levels of atmospheric CO_2 are higher than those in the last 3 million years (Zhang et al. 2013), and these levels are likely to drive changes to climate (Solomon et al. 2009). Although the magnitude of potential climate change may be comparable to variability experienced in the past, the rate of that change is anticipated to be significantly greater (Diffenbaugh and Field 2013), with substantial implications for Montana's forests. Montana's forests will be affected by both direct and indirect effects of climate change. Direct effects are impacts to trees that arise directly in response to changes in temperature and precipitation; indirect effects are secondary impacts, such as increased number of fires associated with warming temperatures, which then affect trees and forests.

In the face of changing climate, forest managers can best maintain stable forest health and product yield by understanding past trends and planning for a range of climate scenarios. The assessments in this chapter are based on the climate trends for which we had sufficient data and climate projections that represent plausible future scenarios, as described in the Climate chapter of this assessment (see Water chapter for snowpack trends and projections) and summarized in Table 4-1.

Table 4-1. Summary of climate metrics and related direct and indirect effects on forests.

Climate Metric— Trend and future scenario	Potential direct effects	Potential indirect effects
Atmospheric CO^2 concentrations have increased; projected to increase leading to future warming	**Positive:** Increased fecundity, photosynthesis, vegetation water use efficiency, and productivity in some species and locations	
Average temperatures have increased with greatest warming in spring; projected to increase with greatest warming in summer and winter and in the southeast	**Positive:** Increased productivity, particularly at higher elevations and cooler areas **Negative:** Increased plant respiration, evaporation and transpiration; reduced productivity in areas with already high temperatures	**Positive:** Increased soil organic matter from increased productivity in some areas; increased nitrogen cycling **Negative:** Decreased soil organic matter from increased decomposition rates; increased soil acidity; reduced soil (and forest) carbon storage
Maximum temperatures have increased with greatest warming in spring; projected to increase with greatest warming in summer and winter and in the southeast	**Negative:** Increased heat stress, reduced growth and productivity, and increased mortality	**Negative:** Increased fire risk
Days above 90°F (32°C) are projected to increase, with greatest increases in the northeast and south	**Negative:** Increased heat stress, reduced growth and productivity, and increased mortality	**Negative:** Increased fire risk
Minimum temperatures have increased most in winter and spring; projected to increase, with greatest increases in January and in the southeast	**Positive:** Longer (or at least earlier) growing season; reduced winter mortality **Negative:** Lower and shorter duration snowpack and shift from snow to rain-dominant precipitation regimes resulting in less water available in summer	**Negative:** Increased potential for pathogen and insect survival
Frost-free days are projected to increase, particularly in the west	**Positive:** Longer (or at least earlier) growing season; increased potential for regeneration success; reduced winter mortality	**Negative:** Increased potential for pathogen and insect survival

Table 4-1. Continued.

Climate Metric— Trend and future scenario	Potential direct effects	Potential indirect effects
Growing degree-days are projected to increase, particularly in the southeast	**Positive:** Increased opportunities for establishment and regeneration; increased productivity	**Negative:** Increased potential for pathogen and insect survival
Average precipitation has decreased in winter, but no significant change in annual mean precipitation potentially because of very slight increases in spring and fall precipitation; precipitation is projected to increase across Montana, primarily in spring; slight decrease in summer precipitation; variability of precipitation year-to-year projected to increase	**Positive:** Increased water availability in spring during critical establishment period **Negative:** Combined with less available water from reduced and shortened snowpack, drier summers could reduce or shift growing season	**Negative:** Increased fire risk
Number of consecutive dry days shows little projected change, however, increased variability in precipitation suggests potential for more severe droughts, particularly in connection with climate oscillations	**Negative:** Reduced establishment, productivity; increased mortality if increased severity of dry spells	**Positive:** Reduced disturbance from fungi **Negative:** Increased fire risk; increased susceptibility to pathogens and insects
Snowpack has declined substantially; projected to continue to decrease	**Negative:** Less available water in summer and potential for increased water stress at same time as highest temperatures	**Negative:** Increased fire risk; warmer and drier soils and reduced mycorrhizal activity

Since 1950, statewide temperatures have shown an upward trend. Although differing somewhat spatially and seasonally, the warming trend is seen across all temperature variables, including annual average, maximum, and minimum temperatures. Similarly, all climate models used in this assessment agree that the average annual temperature in Montana will increase over the next century.

An average statewide increase of 4.5-6.0°F (2.5-3.3°C) is projected for the mid-century and an overall increase of 5.6-9.8°F (3.1-5.4°C) is projected for the end of the century (see Climate chapter for a description of the emission scenarios used to obtain these values). Maximum monthly temperatures are projected to increase, as are extreme heat days (days with temperatures >90°F [32°C]), monthly minimum temperatures, frost-free days, and accumulated growing degree-days.

Changes in precipitation (described in the Climate chapter) are more varied and uncertain. In general, there has been a slight but statistically significant trend of decreasing winter precipitation across the state, averaging -0.14 inches/decade (-0.36 cm/decade) since 1950. Projected future shifts in precipitation are varied, with not all models agreeing on whether precipitation will increase or decrease in Montana. The majority of models suggest a slight increase in total average annual precipitation across the state, largely occurring in spring, particularly in the northwest. The models show less agreement regarding summer precipitation patterns, though a slight majority of models suggest that there may be very small decreases in summer precipitation, particularly in the southeast.

Given these trends and projections for temperature and precipitation, for the remainder of this chapter we consider the impacts of continued warming to Montana forests. In particular, we focus on increasing maximum temperatures in summer and increasing minimum temperatures throughout the winter, with greatest temperature increases in the southern and eastern areas of Montana. We assume a scenario of slightly wetter years on average, with spring precipitation increasing most in the north and western areas, although we assume summers become slightly drier.

Drought has a major impact on forests. An important predictor of future ecosystem drought (defined as ecological drought in the Water chapter) susceptibility is the net balance of water gained through precipitation and water lost through evapotranspiration (the combined effect of water evaporation and the transpiration of water by plants). Predicting how increases in temperature and atmospheric CO_2 may shift evapotranspiration is extremely challenging, especially at regional scales such as Montana. However, it is expected that—given the combination of changes in precipitation variability, changed snowpack, and rising temperatures—future droughts will be more severe when they do occur. Undoubtedly, Montanans will continue to experience periodic drought, particularly in connection with climate oscillations (or equivalently, *teleconnections*, as described in the Climate chapter) (Trenberth et al. 2014). Thus, we discuss the implications of more severe drought, particularly during dry periods that may amplify drought effects, although we do not assume a change in frequency or duration of drought.

It is important to note that current forest conditions will largely determine the potential impacts from current and future climate change. Forest conditions vary across land ownership types, and many Montana forests are under stress due in part to past forest management practices. For example, fire suppression practices on some state and federal lands have led to denser forests, which are more susceptible to fire and stressed by competition and crowding from other trees. Further, harvest practices have shifted the genetic makeup of some forests, potentially reducing their resilience to climate change (see Genetics sidebar).

A note on species-level effects

We do not detail potential responses of individual tree species to climate shifts in this assessment; we instead direct the reader to Chapter 6 in the Northern Region Assessment Program report (Keane et al. forthcoming). That report reviews tree genetics, species distribution, potential adaptive strategies, and susceptibility to drought and disturbance from fire and insects. While the literature is inconsistent about the susceptibility of certain species to direct and indirect impacts of climate change, the relative susceptibility of tree species to drought, fire, and insect/disease has been assessed based on expert opinion (Table 4.2). Species responses will strongly depend on the magnitude of climate change, water availability, management practices, and local conditions.

Table 4-2. Generalized susceptibility of common Montana tree species to drought, fire, and insects and pathogens or disease, rated low to high (mod=moderate) per detailed species climate vulnerability assessment by Keane et al. (forthcoming).

Species	Drought	Fire	Insect/ Disease
Alpine larch	Low	High	Low
Aspen	Low-Mod	High	Moderate
Cottonwood	Low-Mod	Moderate	Low-Mod
Douglas-fir	Low-Mod	Low-Mod	Moderate
Engelmann spruce	Low-Mod	Mod-High	Low-Mod
Grand fir	Mod-High	Mod-High	Mod-High
Limber pine	Low	Mod-High	Mod-High
Lodgepole pine	Moderate	Moderate	Mod-High
Ponderosa pine	Low-Mod	Low	Moderate
Subalpine fir	Low-Mod	High	Moderate
Western larch	Mod-High	Low	Low-Mod
Western white pine	Moderate	Low	Mod-High
Whitebark pine	Mod-High	Moderate	Mod-High

DIRECT EFFECTS OF CLIMATE CHANGE ON FORESTS

Key Messages

- ***Increased temperatures will have positive or negative effects on individual trees and forest-wide processes, depending on local site and stand conditions.*** *In relatively cool and moist areas, increased temperatures can improve reproduction and establishment, lengthen the growing season, and increase forest growth and productivity. Alternatively, in areas that are already warm or projected to see large temperature increases, warming is likely to decrease growth and increase heat- and drought-related mortality.* [high agreement, moderate evidence]

- ***Direct effects of climate change on individual trees will be driven by temperature in energy-limited forests and moisture in water-limited forests.*** *Increased temperatures and water availability could benefit forest regeneration and growth, particularly in higher-elevation forests in the northern and western parts of the state. Alternatively, decreased water availability, such as in Montana's southeast, or south-facing slopes, will likely increase tree mortality.* [high agreement, moderate evidence]

- ***The speed and magnitude of climate change may mean that increased forest mortality and contractions in forest distributions will outpace any gains in forest growth and productivity over the long run, leading to a net loss of forested area in Montana.*** *However, range shift responses will be highly dependent on species and region.* [medium agreement, limited evidence]

The direct effects of climate change on forests include increased temperatures and shifts in precipitation that together can alter humidity, soil moisture, and water stress. These effects result in short-term and long-term impacts to tree establishment, growth and productivity, and mortality. In addition, elevated CO_2 levels may influence forest growth, productivity, and water use.

Direct effects can be beneficial *or* detrimental to forest growth and survival. Each tree species will respond differently to climate variation depending on its specific physiological tolerances. Direct effects overlie existing forest conditions arising from past and future human land-use activities (Moritz and Agudo 2013). Thus, net impacts, whether positive or negative, may be difficult to estimate and will vary substantially across Montana.

Forest patterns and conditions depend on the life cycles of individual trees and forest-wide processes. In the remainder of this section, we review how different aspects of climate may influence three primary life-cycle stages or forest processes: seedling establishment and forest regeneration; tree growth and forest productivity; and tree mortality and forest die-off (findings summarized in Table 4-3). Life-cycle stages and forest processes may occur at different temporal and spatial scales, but are related and we discuss each in turn. We close the section with a discussion of changes in species distribution that might be expected from the direct effects of climate change.

Bitterroot Range.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

Table 4-3. Summary of potential climate-related direct effects to forests.

Direct effect	Possible impacts	Projected net effect
Establishment and regeneration	**Positive:** Higher CO_2 concentrations and temperatures may lead to increased tree fecundity **Negative:** Higher temperatures and reduced water availability could reduce seedling survival	Possible positive or negative effects are superimposed on climate oscillations, such as the Pacific Decadal Oscillation, which can produce decades of cooler and wetter conditions that may be more favorable for establishment and regeneration
Growth and productivity	**Positive:** Increased vegetation water use and increased growth and productivity as a result of longer growing season **Negative:** Reduced growth and productivity in water limited areas	Possible increased growth and productivity concurrent with climate oscillations that increase water availability, particularly at higher elevations and where stand density is low; extreme high temperatures would have net negative impact, regardless of water availability
Mortality	**Positive:** Few opportunities for reduced direct climate effects on mortality but possibility for reduced mortality from indirect effects **Negative:** Increased acute and background mortality from increased temperatures and indirectly from increased disturbance	Increased mortality, although may be driven by indirect effects; patterns of mortality will be dependent on initial stand and local site conditions, but more arid regions more susceptible
Range shifts and forest distribution	**Positive:** Potential range expansion with warmer temperatures and sufficient moisture **Negative:** Potential range contraction where temperature is too high or in water-limited locations	Possible faster range contraction compared to expansion, with net range reduction particularly in drier areas; no clear direction of elevational shifts; responses will be highly species and location dependent

Establishment and regeneration

Although tree recruitment—the process of a seedling becoming established and surviving into adulthood—is affected by many factors, the process is strongly tied to temperature and water availability (Ibáñez et al. 2007). Overall, studies are inconclusive as to net impacts of changing atmospheric chemistry and climate on seedling establishment and growth. Given the climate projections of increased winter and spring precipitation, but drier summers, predicted uncertainties of seedling regeneration are uncertain.

Climate conditions determine the window of time for successful seedling establishment (Ibáñez et al. 2007). Warmer conditions combined with *wetter* winters and springs may lengthen the window for seedling establishment in high-elevation forests, but may not change significantly in lower elevation forests (though it may shift earlier) (Keane et al. forthcoming). However, even with a lengthened window for establishment, warming temperatures alone may cause seedling mortality and failed regeneration as a result of seasonal mismatches in the timing of flowering and seed production (Cayan et al. 2010; Williams et al. 2013). In the short term, warmer temperatures but *drier* summers may increase forest regeneration due to a) increased tree flowering and recruitment, and b) drought-related reductions in canopy cover speeding sapling growth (Galiano et al. 2013; Ibáñez and McCarthy-Neumann 2014; Clark et al. 2016). Additionally, higher CO_2 levels have been shown to increase fertility and seed and pollen production in some trees (Ladeau and Clark 2006). However, in the long term, more severe drought is likely to reduce tree establishment by reducing seed germination, as well as increasing mortality of seedlings and saplings (Kolb and Robberecht 1996; Chmura et al. 2011).

Many responses may be species-specific, for example ponderosa pine seedlings are sensitive to temperature, lodgepole pine seedlings are sensitive to moisture fluctuations (Petrie et al. 2016). Ultimately, in forests not otherwise limited by energy or nutrients variability in moisture availability with natural and climate oscillations may drive establishment success between years (League and Veblen 2006), with indirect disturbance effects (e.g., fires, landslides, insect outbreaks, and pathogen attacks) greatly affecting long-term recruitment success (Clark et al. 2016).

Growth and productivity

Warming temperatures, increased atmospheric CO_2, and longer growing seasons provide opportunities for increased photosynthesis, thereby improving forest growth and productivity (Ehleringer and Cerling 1995; Joyce and Birdsey 1995; Waring and Running 2007; NPS 2010). However, these same changes can also reduce forest productivity, particularly in water-limited systems. Thus, net forest response is uncertain, but likely negative under extreme temperature increases.

Forest productivity will increase up to some optimal temperature and then begin to decline if temperatures continue to rise. This decrease results because plant respiration also increases with temperature, and some of the photosynthetic gains (that lead to increased productivity) are lost through a) growth and maintenance respiration (Ryan et al. 1995), or b) seasonal differences between photosynthetic gains in the spring and increased respiration in the fall. These tradeoffs can result in no net increase in productivity (Piao et al. 2008). Additionally, extremely high temperatures can lead directly to increased water stress because of drier soils. The temperature threshold at which declines would occur is complicated by the fact that elevated CO_2 levels may increase water-use efficiency in plants (Waring and Running 2007) and thereby lower plant water stress (Franks et al. 2013).

Although CO_2 fertilization has likely increased forest growth at a global scale (McMahon et al. 2010), this increase may be evident in only about 20% of forests, with the remaining 80% unable to capitalize on benefits of higher atmospheric CO_2 because of water or nutrient limitations (Gedalof and Berg 2010). A recent study suggests that Montana forests will likely show substantially lower productivity overall given only small projected increases in precipitation (Charney et al. 2016). Reduced snowpack and earlier snowmelt (see Water chapter) may further limit any potential gains in productivity. In general, changes in temperature, precipitation, and snow could alter forest productivity in Montana as described below.

- Forest productivity may increase in montane, subalpine, and alpine areas.—These areas may not exceed optimal temperatures, even under end-of-century projections, and these high-elevation areas should have sufficient moisture with increased winter and spring precipitation and longer snowpack duration, allowing growing seasons to lengthen and forests to benefit from higher atmospheric CO_2 (Keane et al. forthcoming). Gains in forest productivity have already been observed in relatively cooler/wetter sites at higher elevations and northern range limits in other regions (Littell et al. 2008; Bhuta et al. 2009; Salzer et al. 2009; D'Orangeville et al. 2016).
- Forest productivity may decrease in lower elevation, warmer, and drier sites.—Conversely, lower elevation areas are likely to see more extreme high temperatures combined with low soil water availability later in the year, resulting in reduced productivity.

Ultimately, shifts in productivity will be site- and species-specific and vary across years. Above- and below-normal temperature and precipitation years associated with natural climate oscillations may determine whether growing seasons lengthen, contract, or shift in time. But even under ideal temperature and moisture conditions, productivity gains will be dependent on local site conditions, such as where there are sufficient soil nutrients or where stand density is low and little competition exists for available resources (Ford et al. 2016). Further, if extreme heat events increase substantially, impacts will be negative regardless of water availability.

Mortality and die-off

The expected increase in drought severity will increase tree mortality in forests. Already, widespread, catastrophic forest die-off events throughout the western US have been directly or indirectly related to drought (Breshears et al. 2005; Allen et al. 2010; Ganey and Vojta 2011; Worrall et al. 2013). Multiple researchers have shown that extended drought correlates with declining tree growth and increased risk of mortality (Allen et al. 2010; O'Connor 2013; Williams et al. 2013). Similarly, the combination of increased warming and drought conditions is the likely cause of recent rapid increases in background (non-catastrophic) forest mortality rates in Montana and the interior West (van Mantgem et al. 2009). For trees beyond the seedling stage, increased temperatures may be responsible for tree mortality more so than water stress (Luo and Chen 2013), although water stress may have been more important historically (Rapacciuolo et al. 2014).

Initial forest conditions affect levels of tree mortality from direct climate effects. For example, soil type and depth, elevation, and aspect all influence water availability for forests. Stand condition may also increase tree mortality by increasing the likelihood of indirect effects (discussed below). Stand condition is particularly important on state and federal forests where a policy of fire suppression for the last 100 yr has increased tree density and the risk of mortality from defoliating and boring insects, and from wildfire.

Species range shifts and forest distribution

Climate conditions and disturbance regimes largely control plant distributions (ranges). Over the millennia, the main responses of species to climate change has been to adapt to changing conditions, move to a new site (range shift), or go extinct (Davis and Shaw 2001). Although many tree species in Montana are relatively plastic—meaning they can adapt in the short term to a wide range of climate conditions—this plasticity could be challenged by severe or prolonged drought or substantially modified disturbance regimes (Allen et al. 2010). Long-term adaptability is determined by the genetic diversity of forests and individual species (Davis et al. 2005), both of which may have been reduced by lack of understanding in the past of how forest management activities affect forest genetics (see Genetics sidebar).

Some evidence exists that tree ranges are already shifting to colder locations in the Pacific Northwest (Monleon and Lintz 2015). However, climatically suitable places are often geographically limited, and alpine vegetation may be running out of mountain as it seeks colder climes (Gottfried et al. 2012). To complicate matters, the optimum elevations for some plant species are shifting downhill tracking changes in water availability, as opposed to simply moving uphill, tracking changes in temperature (Crimmins et al. 2011). Divergence in the direction between optimal temperature and moisture conditions may make it difficult for trees to stay in equilibrium

The Importance of Genetic Diversity

Forest genetics—the genetic variation and inheritance of various genes of forest trees—will primarily determine a forest's ability to adapt to climate change over the long term. Genetic diversity largely determines a species' ability to survive extreme events and adapt to changing conditions (Ledig and Kitzmiller 1992). Historically, the high genetic diversity of many tree species allowed forests to tolerate a wide range of environmental conditions and adapt to shifts in climate (Westfall and Millar 2004; Nicotra et al. 2015).

However, it is unclear whether species with even high levels of genetic and physical diversity can adapt fast enough to the rapid and extreme shifts in climate that are projected over the next century (Vose et al. 2012).

Human actions have undoubtedly altered forest genetics, at least in part through silvicultural practices. Because physical characteristics (e.g., tree height or basal diameter) are used to select trees for harvest, silvicultural practices can alter forest genetics, which are the bases for these physical differences. Selective harvesting may have substantially altered the presence of rare genetic characteristics (Cheliak et al. 1988; Schaberg et al. 2008), which are often those needed by a species to adapt to climate change.

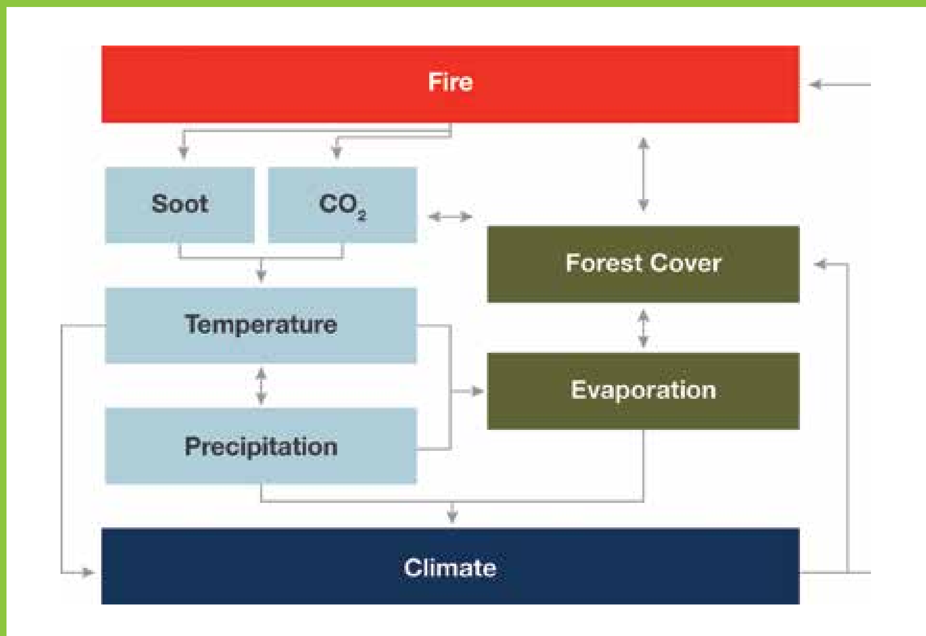
Even though data regarding trends in forest genetic diversity are scarce, a general consensus exists that natural genetic diversity may be at risk globally as a result of human activities (Schueler et al. 2012; Alfaro et al. 2014; FAO 2014). Managing forests to retain or increase this diversity is one of the best options for conservation.

with favorable climate conditions (Dobrowski et al. 2013). Regardless of direction of range shift, there is concern whether tree species can disperse and regenerate quickly enough to keep pace with the magnitude and rate of projected climate changes (Zhu et al. 2012). Although dynamic vegetation models tend to predict an overall expansion of cool forests and woodlands (Shafer et al. 2015), some tree species may actually experience reduced ranges due to geographical obstacles to range expansion in response to climate (Coops and Waring 2001). Current best global estimates suggest that forest mortality is outpacing benefits from increased tree productivity due to increased atmospheric CO_2 (Allen et al. 2010), signifying an overarching contraction of forest range (Dobrowski et al. 2015).

Feedbacks

Forest responses to climate change may be complex due to feedbacks, which are the interplay between different climate change-related effects. One effect may amplify or diminish another effect, and that interaction has the potential to result in changes that are non-linear, unpredictable, and even dramatic.

For forests, a notable challenge will be understanding and preparing for interactions in disturbances (Buma 2015). For example, if a fire burns a forest, it will release stored carbon. If many fires burn globally, there will be an increase in atmospheric CO_2, the main driver of climate change. Further, more fires would mean fewer trees and that could mean that less water vapor transpired into the air, resulting in drier conditions. Drier and warmer conditions would lead to more fires—a positive feedback loop where changes are amplified. In a negative feedback loop, changes are diminished or reach a steady state. For example, increased atmospheric CO_2 may increase forest productivity. More trees would sequester more atmospheric CO_2, thereby reducing atmospheric CO_2 and dampening the initial CO_2 fertilization effect.



A simplified example of the feedbacks between wildfire and climate (adapted from Vose et al. 2016).

Feedbacks may occur between resources as well, for example, between forests and water quantity. The feedbacks are not always as assumed. For example, forest die-off caused by drought has, in some areas, been shown to reduce streamflow as opposed to increasing it, as might seem more intuitive (Guardiola-Claramonte et al. 2011).

Even where ecologists recognize a feedback, they often do not understand all the connections or even if the interplay between components leads to positive or negative outcomes. It is also likely that many feedbacks exist that are currently unknown. Regardless, scientists believe that feedbacks are likely to increase the ecosystem impact of individual disturbances, which may have substantial implications for changes in distribution and heterogeneity of forests in the future (Bonan 2008; Vose et al. 2012; Richardson et al. 2013).

INDIRECT EFFECTS OF CLIMATE CHANGE ON FORESTS

Key Messages

- *An increase in fire risk (i.e., probability of occurrence)—including an increase in size and possible frequency and/or severity (i.e., tree mortality)—is expected in the coming century as a result of a) prolonged fire seasons due to increased temperatures, and b) increased fuel loads from past fire suppression. Spatial patterns of fire activity will be complex and dependent on disturbance history and current stand condition. Fire risk may increase in all forests; fire severity may increase the most in lower elevation forests.* [high agreement, robust evidence]

- *Rising temperatures are likely to increase bark beetle survival* [high agreement, strong evidence]*, but climate-induced changes to other insects and forest pathogens are more varied and less certain* [medium agreement, moderate evidence]*. Climate change effects are difficult to forecast because of the interplay between climate-driven changes in insect or pathogen behavior and changes in host tree susceptibility.*

- *There may be a reduction in the amount of carbon stored in forests. Rising temperatures and increased atmospheric CO_2 can increase forest productivity and thus the carbon stored in organic matter. However, warmer temperatures can also reduce soil carbon through increased decomposition rates. Overall, increased tree mortality from increased forest disturbance may cause a reduction in forest carbon storage.* [low agreement, limited evidence]

The direct effects of increasing temperature and precipitation may result in the expansion and/or contraction of certain forest types in certain regions of Montana. However, the indirect effects of climate change on forests, such as changing wildfire and beetle outbreak severity, are already having a large impact on the health of Montana's forests and in some instances these impacts are easier to predict. These direct and indirect impacts of climate on forests may be exacerbated or ameliorated by human land-use activities in the past and moving forward.

Our scientific understanding of disturbance associated with extreme weather events limits our ability to project landslides, blow downs, ice storms, and other such events in the future. In this section, we will consider the impact of changes in fire, insect, and pathogen outbreaks on forests, as well as on soil and carbon storage, for which we have better capacity for forecasting (Table 4-4).

Table 4-4. Summary of potential climate-related indirect effects to forests.

Indirect effect	Possible impacts	Projected net effect
Disturbance: fire	**Positive:** Increased forest heterogeneity (long-term, post-burn) **Negative:** Decreased forest diversity and heterogeneity (immediately post-burn); increased social and economic impacts from fire; increased release of forest carbon	Increased fire severity resulting primarily from warmer weather and past fire suppression; increased release of forest carbon from fire
Disturbance: pathogens	**Positive:** Some pathogen species may decline and result in decreased forest mortality **Negative:** Some pathogens species may increase and result in increased forest mortality and increased susceptibility to beetle attack	Uncertain climate effects on pathogens, dependent on moisture regimes, pathogen species, and host species
Disturbance: insects	**Negative:** Increased forest mortality; reduced forest diversity with shift towards non-host tree species	Increased temperatures likely to result in increased insect disturbance, but dependent on elevation, insect species and host availability
Soil responses and carbon storage	**Positive:** Increased organic matter if increased productivity; increased nitrogen availability **Negative:** Decreased organic matter (with increased decomposition rates); decreased mycorrhizal support; increased soil acidity; increased release, or decreased removal, of atmospheric CO_2	Uncertain climate effects on soil responses, but projected reductions in soil and forest carbon storage

Disturbance resulting from fire

Fire is a critical component of forest dynamics; it has historically been the dominant disturbance in forest ecosystems in the West (Baker 2009; Marlon et al. 2012). Fire regimes are characterized by interactive relationships, across temporal and spatial scales, between climate and weather, vegetation and fuels, and ignition sources and topography (Parisien and Moritz 2009). Fires have burned frequently and widely across Montana (Figure 4-4), but the area burned and the severity of fire, often measured by reduction in biomass or tree mortality, has varied across the state. For example, from 2003-2012, fire severity was greatest along the eastern border and southern portion of the northwestern climate division (Figure 4-5) (Berner et al. forthcoming).

Historical and Recent Fires in Montana

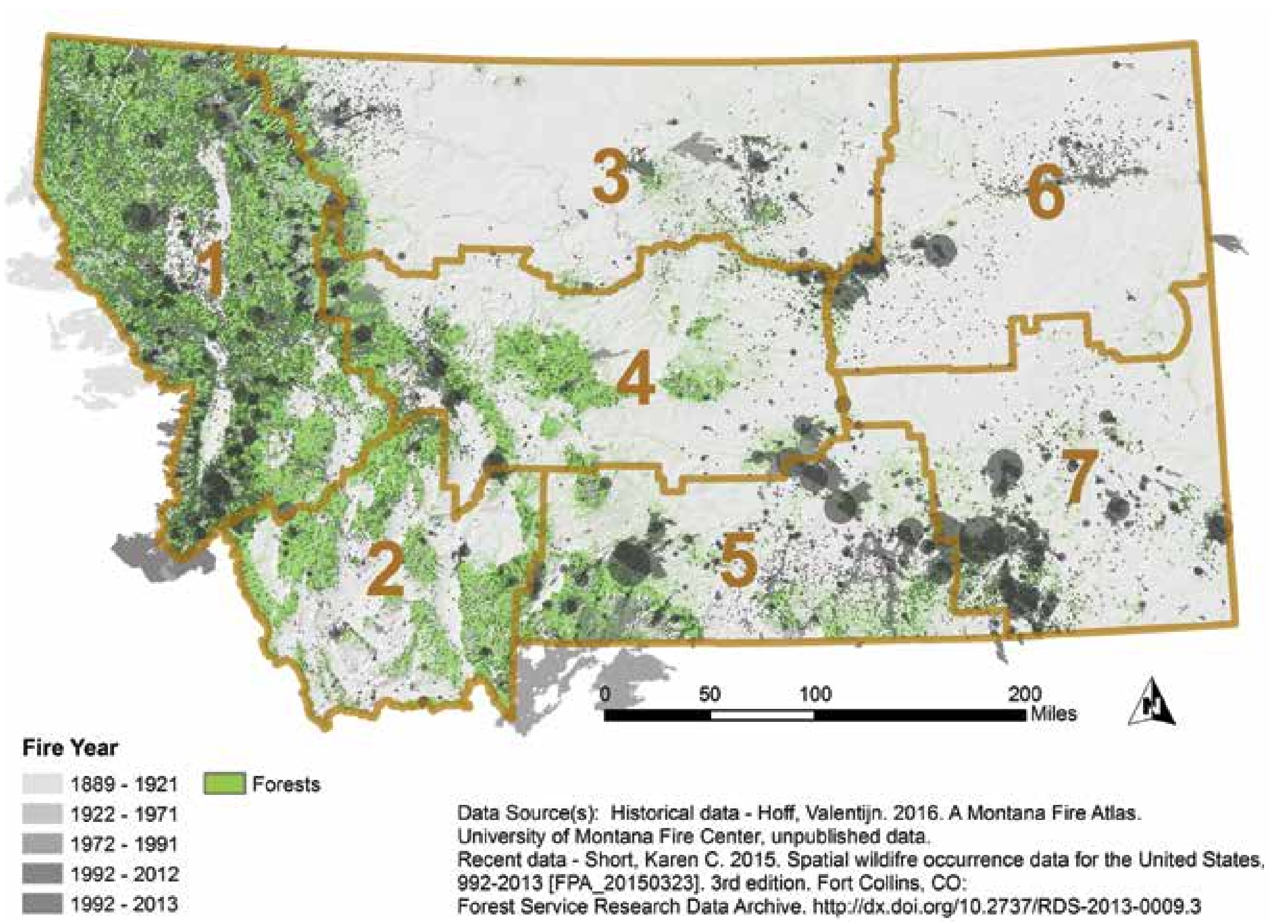


Figure 4-4. Extent and location of historical and recent fires in Montana, 1889-2013. Historical data (1889-1991) are mapped as actual fire boundary polygons as available. Recent data (1992-2013) are mapped as circles approximating burned area. Recent fires too small to be seen by area are mapped as points. Forests are shown in green. Fire data represent primarily forest fires, but may include grassland and other fire types. Brown boundaries delineate climate division. Data and map from Hoff (forthcoming).

Fire Severity

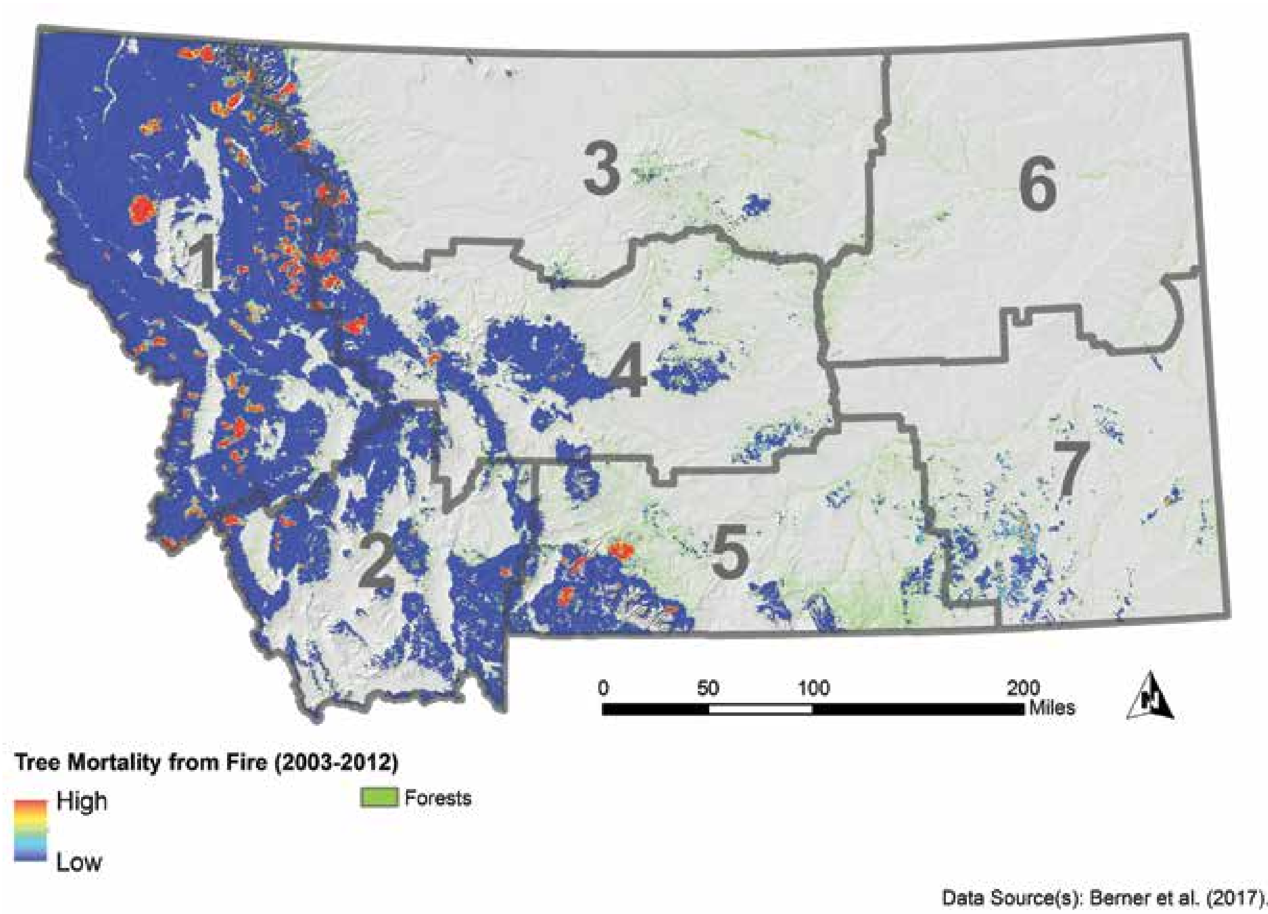


Figure 4-5. Fire severity (measured as total carbon stored in aboveground tissues killed by fire) estimated for 2003-2012, a relatively dry decade. Adapted from Berner et al. (forthcoming).

Broadly, seasonal average temperature and precipitation patterns limit both the length of the fire season and environmental conditions during the fire season. Over the long term, climate also determines the distribution of vegetation and possible fuels (Power et al. 2007; Marlon et al. 2008). Fire occurrence increases during hotter, drier conditions (called *fire weather*) (Flannigan and Harrington 1988). Thus, the fire season in Montana typically extends from late June through October at lower elevations, with shorter seasons at higher elevations where snowpack can persist into July (Keane et al. forthcoming). Variation in fire regimes in the West have historically been associated with climate oscillations (Heyerdahl et al. 2002). In Montana, increased fire frequency is associated with warmer spring temperatures and drier summer conditions (Heyerdahl et al. 2008; Morgan et al. 2008), often associated with El Niño. The phase of the Pacific Decadal Oscillation that leads to warmer conditions may also prolong and intensify the fire season (Heyerdahl et al. 2008; Jolly et al. 2015; Abatzoglou and Williams 2016), and it is clear that years with protracted or widespread wildland fire or increased fire severity are correlated with drought (Littell et al. 2009; van Mantgem et al. 2013). Warmer, drier climate phases can particularly increase fire risk when they follow cooler, wetter conditions that increase fire fuel availability via increased vegetation growth and reduced fire activity (Heyerdahl et al. 2008). Topography can also influence fire behavior by determining local microclimates—for example, variations in local snowpack, temperature, and humidity (Holden and Jolly 2011)—or alignment with prevailing winds (Sharples 2009) which increase fire spread.

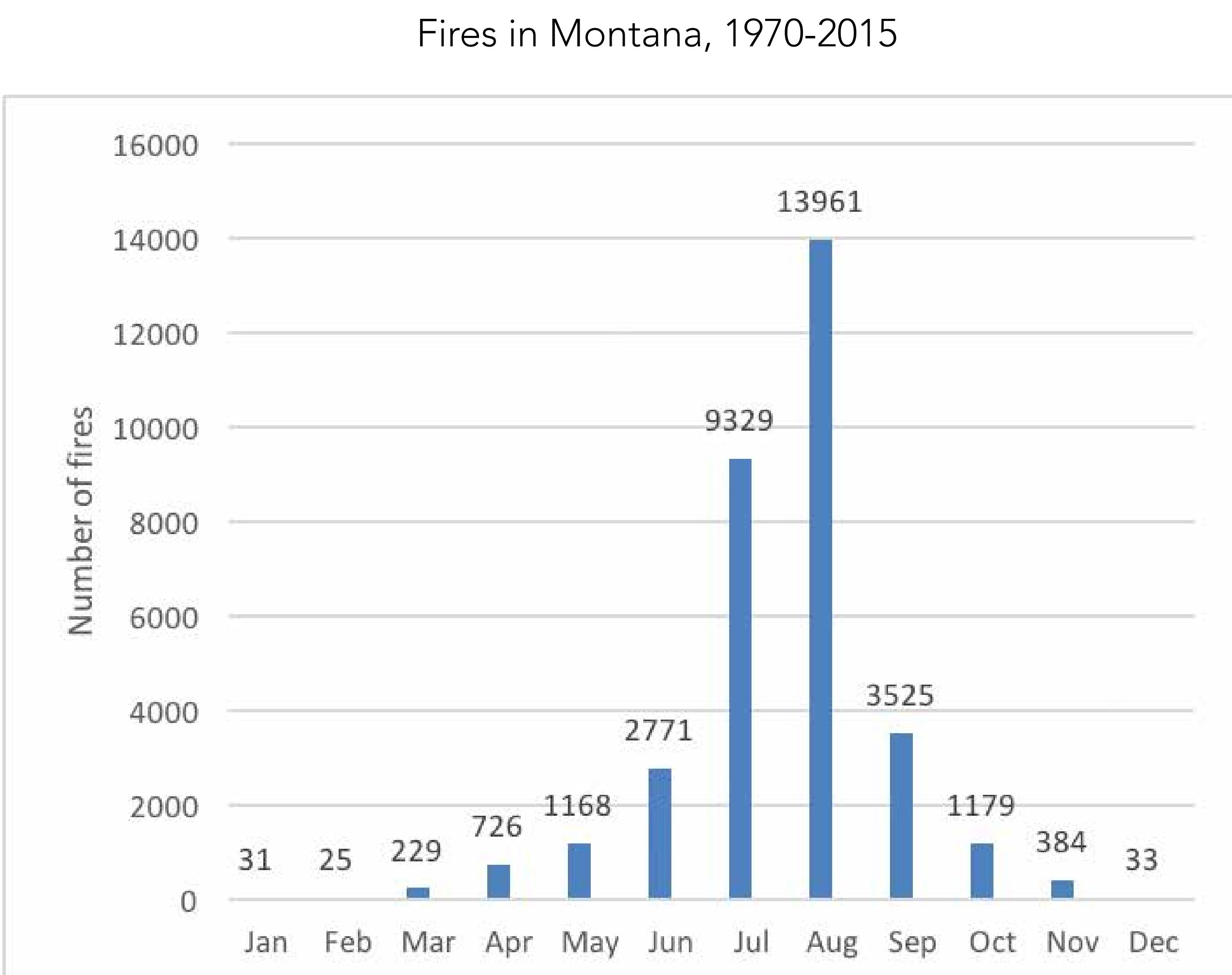


Figure 4-6. Number of fires in Montana, 1970-2015, by month of occurrence (NIFC undated).

Across Montana, conditions that lead to high fire risk (i.e., likelihood of occurrence) are becoming more common: seasonal maximum temperatures are increasing, snowmelt is occurring earlier, minimum relative humidities are decreasing, and fuels are becoming drier (Jolly et al. 2015; Seager et al. 2015). Combined, these factors have led to the fire season lengthening globally between 1979 and 2013 (Jolly et al. 2015). In addition, across the western US, fuel loads and tree densities have increased as a result of fire suppression practices beginning in the 1920s (Parks et al. 2015), as well as other land uses, such as timber harvest and grazing (Allen et al. 2002; Swetnam and Betancourt 2010). As a result, it is clear that climate change, combined with greater fuel loads, has increased western fire activity over the past 30 yr (Westerling et al. 2006; Miller et al. 2008; Dennison et al. 2014; Abatzoglou and Williams 2016).

Combined with fuel loads, higher evapotranspiration rates and resulting shifts in water balance may be the best predictor of increased fire risk and fire severity in the future under a changing climate (Littell and Gwozdz 2011; Abatzoglou and Kolden 2013). Yet, climate change effects on overall water balance are uncertain. Rising temperatures should increase evapotranspiration, but plants may adapt by reducing water lost to transpiration. Additionally, vegetation patterns and forest connectivity, and the feedback between these and fire, play an important role in how climate-driven changes in fire regimes are likely to play out over the long term (McKenzie and Littell 2017).

Although fire modeling is complex and models specific to Montana climate divisions are unavailable, recent studies suggest likely trends for the state. McKenzie and Littell (2017) project that water balance deficits will increase, likely leading to increased area burned. Jolly et al. (2015) project that warmer summers and reduced moisture will also continue to lengthen fire seasons. Modeling work by Schoennagel et al (2004) and Rocca et al (2014) for the Rocky Mountains projects changes in fire frequency (assumed by the authors to be related to the long-term increase in probability of fire occurrence) and severity in western Montana. Those changes, for broad forest-type categories over the short and long terms, are shown in Table 4-5. These projections likely are generally applicable to other parts of Montana, as well.

Table 4-5. Potential changes in fire regimes under a changing Montana climate, with greater certainty in short-term, versus long-term, changes.

Forest type	Short-term impact	Long-term impact
In lower montane forests, primarily consisting of ponderosa pine, co-dominated by Douglas-fir or western larch	Increased fire weather could lead to short term increased fire frequency and fire severity, particularly where fire suppression efforts have increased fuel loads	Reduced fire frequency and increased fire severity in the long-term.
In cooler and wetter upper montane forests	Increased fire frequency and severity	Increased fire frequency but uncertain implications for changes in fire severity
Subalpine forests, dominated by Engelmann spruce and subalpine fir species or by lodgepole pine mixed with limber pine or whitebark pine in drier sites	Increased fire frequency with no change in fire severity	Increased fire frequency with no change in fire severity

Disturbance resulting from pathogens and insects

Dale et al. (2001) estimated that impacts from forest pathogens and insects result in greater economic costs to US forests than any other type of disturbance. Pathogens include fungal, bacterial, and viral infections, as well as parasitic plants (and here we include general forest disease in our definition of forest pathology). Pathogens can affect different parts of a tree, such as trunk and branch cankers, root pathogens, and foliar (leaf or needle) diseases.

Many of these insects and pathogen species are native to Montana's forests. For example, mountain pine beetle (*Dendroctonus ponderosae*), Douglas-fir beetle (*Dendroctonus pseudotsugae*), and the western spruce budworm (*Choristoneura occidentalis*; a defoliator) are important in determining forest distribution, structure, and regeneration. Although these native insects are unlikely to annihilate their host species, recent extreme outbreaks have severely impacted some western forests. Non-native species, conversely, have the ability to eradicate their host species locally. For example, white pine blister rust, caused by the fungus (*Cronartium ribicola*), has put western white pine, limber pine, and whitebark pine in some areas of Montana in jeopardy (Smith et al. 2008).

Using aircraft, the US Forest Service has conducted insect and disease detection surveys for over 50 yr (USFS 2016). Nearly 14 million forested acres (5.7 million ha) in Montana showed visual signs of disease or insect disturbance between 2000-2015 (Figure 4-7), and that number is assumed to be conservative. Bark beetles and defoliators have been the primary cause of biotic disturbance as identified from aerial surveys (Figure 4-8). Based on other, non-visual, approaches to estimate risk from pathogens and insects, root disease appears to be another major threat to Montana's forests (Krist et al. 2014).

Climate change can influence forest pathogens and insects through three primary mechanisms: 1) altering pathogen or insect abundance and distribution via physiological effects; 2) altering tree defenses; and 3) altering interactions between pathogens, insects, and their competitors (Weed et al. 2013). In addition, climate change can alter the distribution and presence of host species.

The interplay between these mechanisms complicates efforts to forecast the potential effects of climate change on pathogens and insects. Soil water deficits, from increased temperatures and reduced precipitation, can result in larger pathogen populations and lower tree and forest defenses against pathogens (Lorio 1993; Chakraborty et al. 2008). Many pathogens tolerate greater water stress than the trees they infect, and some fungi that commonly occur in or on trees become pathogenic when a tree is water stressed (Desprez-Loustau et al. 2006). Beetle activity is also strongly tied to climate, and warmer temperatures speed up reproduction times, extend growth periods, and increase probability of beetle survival (Mitton and Ferrenberg 2012; Bentz and Jönsson 2015; Bentz et al. 2016). Further, trees stressed by drought are more susceptible to beetle invasions (Creeden et al. 2014). Field studies suggest that recent mountain pine beetle outbreaks correlate with mean August temperatures >59°F (15°C) and that outbreak size is correlated with minimum winter temperatures and drought conditions in previous years (Preisler et al. 2012).

Forest Disturbance

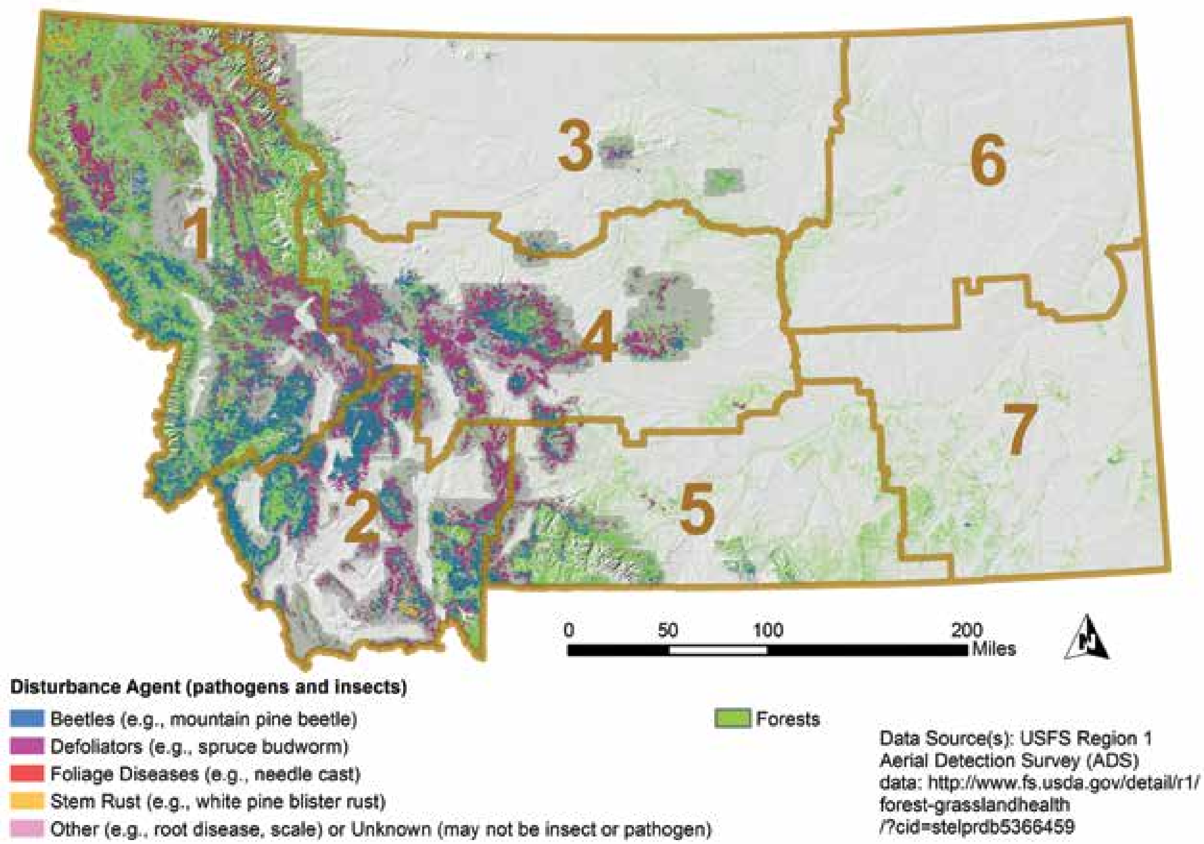


Figure 4-7. Recent Montana forest disturbance as visually estimated from aerial surveys in 2000-2015 (USFS 2016). Forests are shown in green. Darker gray background represents area surveyed in 2015; not all areas were surveyed in all years and many pathogens cannot be visually estimated. Brown boundaries delineate climate divisions.

Forest Disturbance

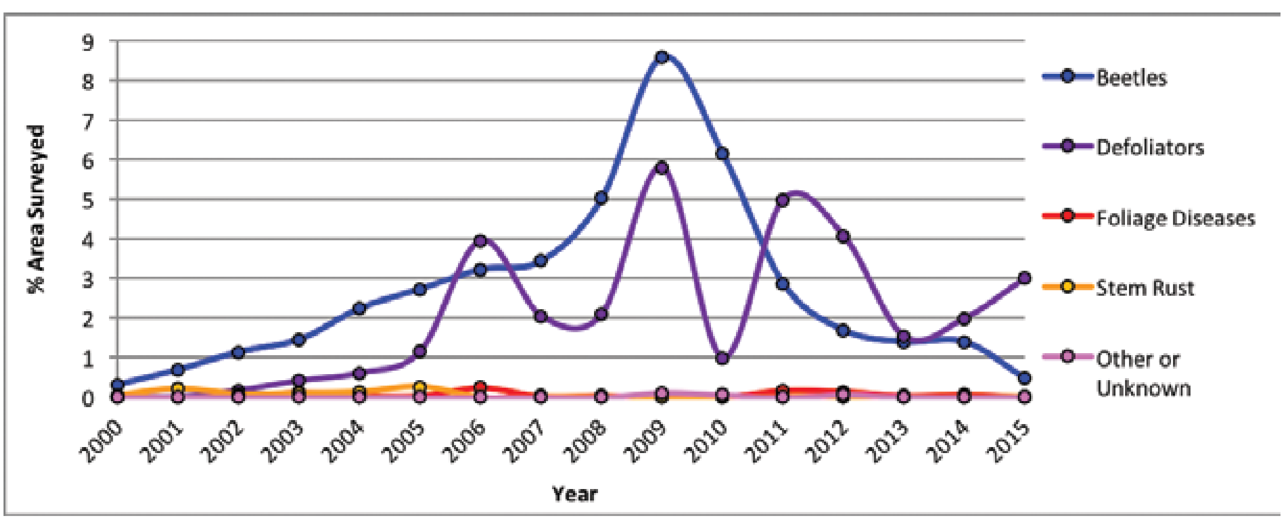


Figure 4-8. Forest disturbance in Montana from 2000-2015 by type of visually surveyed pathogen or insect as percentage of the total area surveyed from USFS (2016) Aerial Detection Survey data.

Projections of continued forest mortality from pathogens and insects suggest that substantial portions of western Montana are at high risk regardless of climate change (Figure 4-9) (Krist et al. 2014). Krist et al. (2014) suggest that expected climate changes would increase pathogen and insect risks to forests beyond those mapped in Figure 4-9 or, at a minimum, alter the spatial patterns of risk.

Forested Areas at High Mortality Risk

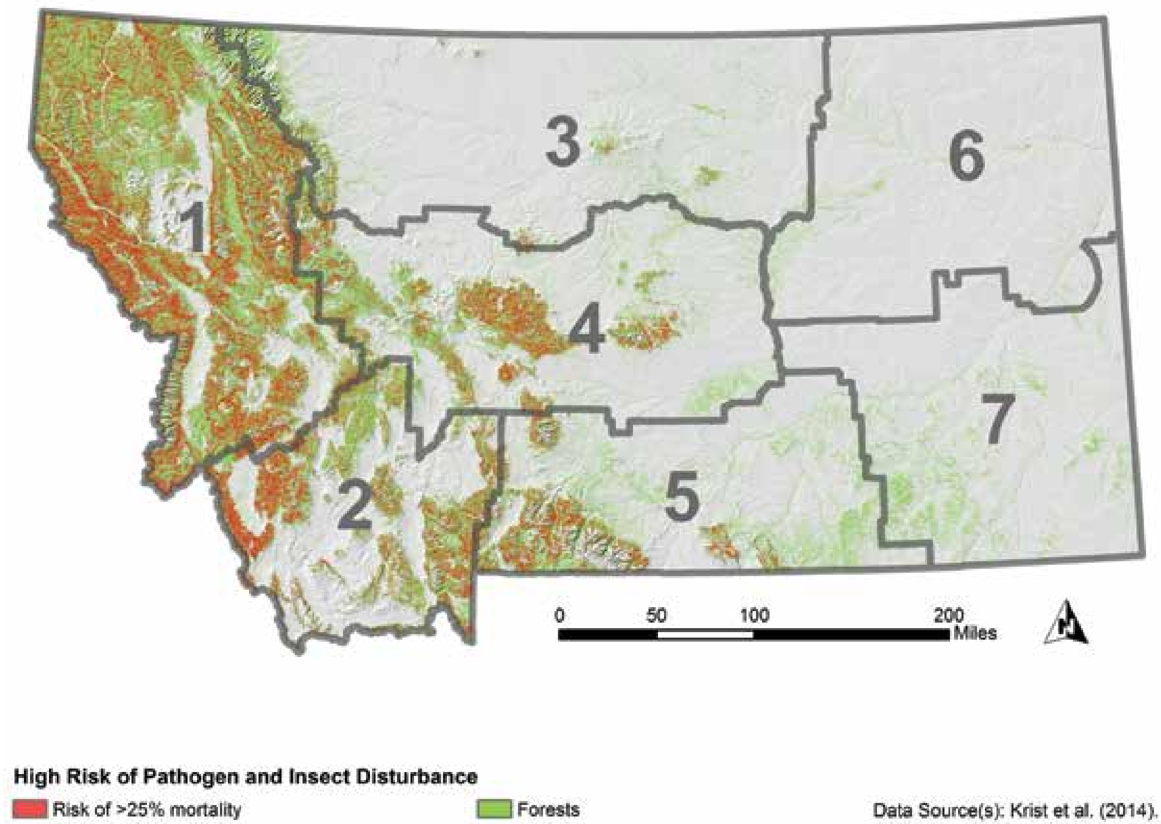


Figure 4-9. Forested areas (green) at high risk of mortality (red) from combined insect and pathogen attacks from the National Insect and Disease Risk Map (Krist et al. 2014). This map does not consider increased risks from projected climate changes. Areas in red are locations where it is estimated that 25% or more of live trees with a diameter of greater than 1 inch (2.5 cm) are at risk of mortality by 2027 from insects and disease.

Changes in pathogen activity may be most strongly linked to shifts in precipitation patterns and moisture availability. For example, Sturrock et al. (2011) estimate that a) Dothistroma needle blight (*Dothistroma septosporum or D. pini*), whose primary host in Montana is ponderosa pine, will have reduced or increased impacts, depending on warmer and drier or wetter conditions, respectively; and b) Armillaria root disease (*Armillaria* spp.), which generally affects Douglas-fir and grand fir, will have increased impacts under warmer, drier conditions, but no change under warmer, wetter conditions. Sturrock et al. (2011) also state that the implications of climate change for white pine blister rust are uncertain, but suggest decreased impacts under a warmer, drier climate, and no change under warmer, wetter conditions because infections require both moist and cool environments.

It appears more certain that a warming climate will increase insect-related forest mortality, depending on the presence of susceptible host trees. Already, warming temperatures have expanded the range of beetles (Carroll et al. 2006), and the largest recorded bark beetle epidemic in western forests has occurred in the past 15 yr. Higher temperatures, if large enough, lead to more severe droughts as water is more rapidly and completely evaporated from soils and streams, which may in turn make forests more susceptible to western spruce budworm outbreaks (Régnière et al. 2010; Flower et al. 2014).

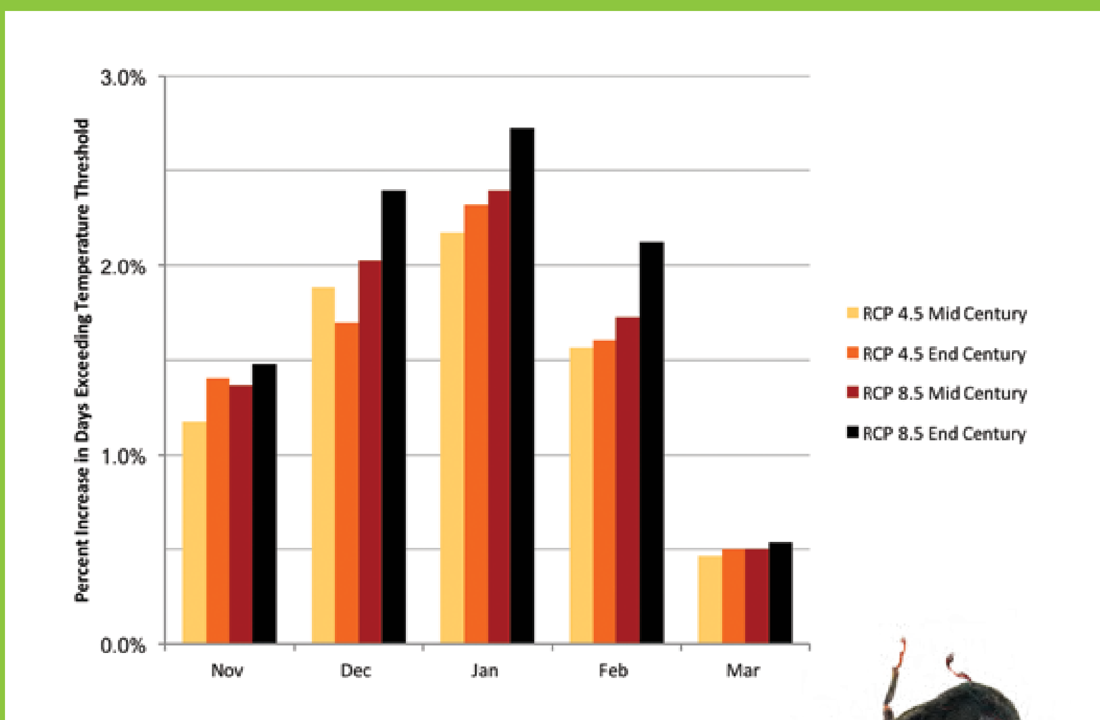
Future of the Mountain Pine Beetle in Montana

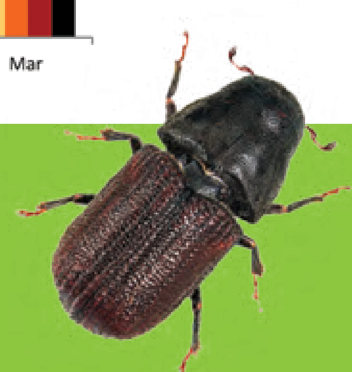
*The mountain pine beetle (*Dendroctonus ponderosae*) epidemic is currently on the wane in Montana because of the reduction of susceptible host trees. We project, however, that rising winter temperatures will result in increased mountain pine beetle populations. Those increases will result from fewer cold snaps, and hence substantially decreased likelihood of seasonal mountain pine beetle die-off.*

We came to that conclusion using field data from Idaho (Régnière and Bentz 2007)—to assess threshold cold temperatures by month (beetles adapt to colder temperature as the winter progresses) that cause approximately 50% mortality in mountain pine beetle populations—combined with projected future air temperatures. For air temperatures, we used four climate scenarios, as described in the Climate chapter, and projected the number of days that are likely to exceed those threshold winter temperatures in the future. Higher winter temperatures, then, equate to reduced winter die-off (i.e., larger populations) of mountain pine beetles.

The figure below shows that for all four temperature scenarios studied in this assessment, warm winter days, above the temperature threshold necessary to kill about half of the mountain pine beetles, will occur more frequently. In other words, warming winter temperatures are projected to increase mountain pine beetle survival.

Our assessment did not show substantial differences across elevations (we considered low, moderate, and high elevations for known pine locations), but other studies have (Hicke et al. 2006; Raffa et al. 2013; Bentz et al. 2016). All insects have different survival strategies and climate tolerances, and even the mountain pine beetle, about which much is known, has a very complex life history (Bentz and Mullins 1999). Thus, impacts could be greater than would be indicated by only considering warmer winter temperatures (Buotte et al. 2016). However, the mountain pine beetle provides a good example of how potential changes in temperature may impact insect species that disturb Montana forests.





(right) Mountain pine beetle (*Dendroctonus ponderosae*). (above) Percent increase in number of days per month exceeding the threshold cold temperatures necessary to cause approximately 50% mortality in mountain pine beetle populations as projected under two greenhouse gas emission scenarios (i.e., representative concentration pathways; see Climate chapter) at mid century and end-of-century.

Soil responses, nutrient cycling, and carbon storage

Soils that are high in organic matter support forest resources by providing moisture, necessary nutrients, and physical support; filtering of toxics and other unwanted compounds; and helpful biota such as mycorrhizae, which are a symbiotic relationship between fungi and roots that help a tree absorb nutrients and water. Soils high in organic matter also store more carbon. Climate change can affect all of these soil functions.[22]

Changes in soil temperature and moisture can have substantial impacts to forests, although the direction of change and resulting impacts are uncertain. For example:

- Soil decomposition rates may increase with high temperatures, reducing the quality and quantity of soil organic matter (Keane et al. forthcoming). Similarly, wet soils can increase decomposition rates, but it is unknown whether soil moisture will increase or decrease under projected climate changes for Montana. Alternatively, increases in forest productivity resulting from increased atmospheric CO_2 can increase litter and soil organic matter.

- Nutrient cycling may be affected by rising temperatures that, in turn, can increase microbial activity. This feedback has the potential to increase nitrogen deposition, providing more of a nutrient critical to tree growth (Melillo et al. 2011). Warming temperatures can also increase nitrogen export (reduction). Recent work by Brookshire et al. (2011) suggests that climate change-driven loss of soil nitrogen could outpace deposition by 3 to 1.

- More important may be how multiple, climate-related effects interact to impact soil resources. For example, increased disturbance from fire or insects could reduce forest canopy shading, thereby further compounding the effects of rising air temperature on soil temperatures. Increased temperatures and reduced water, happening concurrently, can decrease mycorrhizal colonization of tree roots (Compant et al. 2010), exacerbating a tree's susceptibility to pathogens.

Carbon storage may also be impacted by climate change. At a global scale, almost 45% of the total forest storage of carbon is in soils, with most of the rest (approximately 42%) stored in live woody biomass (Bonan 2008; Pan et al. 2011). Global forest carbon storage has been increasing over the past 50 yr in response to increased nitrogen deposition and atmospheric CO_2 concentrations, despite a worldwide reduction in forested area (Bellassen and Luyssaert 2014). The same trend is seen in the USFS's Northern Region (northeastern Washington, northern Idaho, and Montana) between 1990-2013, although the trend is small and there are substantial differences among forest types (USFS 2015).

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[22] This report focuses on climate change impacts, not mitigation. Still it is important to recognize that forests are a key carbon sink, and have the potential to reduce atmospheric CO_2 through carbon sequestration (i.e., the removal of carbon from the atmosphere to be stored in an alternative form) (Ingerson 2007; Pan et al. 2011). Pan et al. (2011) estimated that forests offset 13% of carbon emissions in North America. Birdsey (1992) estimated Rocky Mountain forests make up about 15% of total US forest carbon storage.

Researchers debate whether increasing temperatures will increase or decrease carbon storage (Davidson and Janssens 2006). With rising temperatures, carbon storage will increase due to increasing forest productivity (assuming adequate water and nutrient availability) (Finzi et al. 2006; Norby et al. 2010; Garten et al. 2011), but decrease due to increasing microbial respiration, which in turn releases CO_2 from the soil. Changes in disturbance regimes (e.g., increased fire frequency or tree mortality from insects) could also result in release of carbon currently stored in forests (Baldocchi 2008; Kurz et al. 2008; Loehman et al. 2014). Overall, carbon models suggest that increased fire and bark beetle outbreaks are likely to reduce carbon storage in western forests (Metsaranta et al. 2010; Westerling et al. 2011), and some research suggests recent steep declines in forest carbon storage in the Rocky Mountains as a result of higher rates of disturbance relative to historical values (Wear and Coulston 2015).

ADAPTATION STRATEGIES FOR A CHANGING CLIMATE

Managers should consider multiple scenarios of potential climate shifts and contemplate a suite of adaptation strategies. Vose et al. (2012) suggest four general types of adaptation options in managing forests for the potential impacts of climate change:

1. Promote resistance.—Enhance ability of species of system to resist forces of climate change;
2. Increase resilience.—Enhance capacity of system to absorb impact without substantial changes to processes and functionality;
3. Enable ecosystems to respond.—Assist a system's transition to an altered state that is adaptive to a changed climate while minimizing disruptive outcomes; and
4. Re-align highly altered ecosystems.—Use restoration techniques to allow a system's function to continue through changing climate conditions.

We recommend a bet-hedging approach, understanding the range of potential options and their possible consequences, and selecting among those that provide the most likely benefit given future uncertainty. We list many potential specific adaptation strategies in Table 4-6. Several guidebooks exist for developing adaptation options on forested lands; these include *Responding to Climate Change on National Forests* (Peterson et al. 2011), *Climate Change in Forests of the Future* (Millar et al. 2007), and *Forest Adaptation Resources* (Swanston et al. 2016).

Table 4-6. General adaptation strategies to increase resilience of forests to climate change and variability.

Adaptation option	Time period	Examples (further reading)
Increase genetic and phenotypic diversity	Mid to long term	• Breed for climate resilience and disease resistance • Plant from multiple species, seed sources, and climate zones, particularly from locally-adapted sources • Manage to maintain genetic diversity and phenotypic plasticity • Create opportunities for rapid natural selection for species with high predicted potential for adverse impacts from climate change (Sturrock et al. 2011; Erickson et al. 2012; Alfaro et al. 2014; FAO 2014)
Improve forest structure, diversity, and resilience	Long term	• Plant various species in microsites (small areas with locally variable climate, topographical, and soil conditions) with existing species mix as guide • Plant drought tolerant and native species • Retain diversity of species and promote legacy trees • Manage or restore mosaic (variable pattern of species and ages) and maintain or improve landscape connectivity • Plant in asynchronous rotations and manage for diverse age classes • Thin, plant, and use prescribed fire to favor species adapted to disturbance (Millar et al. 2007; Vose et al. 2016; Keane et al. forthcoming)
Improve establishment	Short to long term	• Plant drought-tolerant species in years with strong El Niño forecasts, particularly during Pacific Decadal Oscillation warm phase; plant trees that require sufficient water during establishment in La Niña years and during Pacific Decadal Oscillation cool phases • Focus planting more in spring as fall planting becomes more difficult with reduced soil moisture and test different planting timings as springs shift earlier
Improve water availability	Long term	• In snow-dominant locations, reduce canopy cover on north slopes (reduce interception of moisture by canopy), retain canopy cover on south slopes (increase shading), in all locations maintain sufficient shading on south slopes to retain soil moisture

Table 4-6. Continued.

Adaptation option	Time period	Examples (further reading)
Improve soil quality	Mid to long term	• Alter timing of logging to reduce soil compaction • Retain woody debris to retain soil moisture and promote nutrient cycling
Reduce fire risk and fire severity	Mid to long term	• Apply additional efforts for fire prevention in drier, warmer years; allow spot burning in cooler, wetter years • Use prescribed fire and thinning to minimize fuel loading and favor fire-resistant species (Vose et al. 2016; Keane et al. forthcoming)
Manage forest diseases	Mid to long term	• Monitor, forecast, and plan regarding forest diseases and use an adaptive management framework • Ensure management activities do not spread disease • Breed for increased disease resistance (Sturrock et al. 2011)
Consider assisted migration and adaptation	Mid to long term	• Assisted adaptation—often defined as management to assist gene flow or selection for specific genetic traits—may be a more useful tool than assisted migration whereby a species is deliberately moved to a different habitat; carefully consider implications of either action • Identify potential climate refugia to focus restoration efforts • Plant a mix of seeds genetically selected and adapted to likely future and current conditions (McLachlan et al. 2007; McKenney et al. 2009; Aitken and Whitlock 2013; Alfaro et al. 2014)
Manage forest carbon (mitigation)	Mid to long term	• Planting new trees to increase forested area • Increase carbon storage in existing forests (e.g., replace dying stands, manage for maximum productivity and reduced fire risk via pre-commercial thinning[23]) • Use of wood as biomass energy (McKinley et al. 2011; Bellassen and Luyssaert 2014)

[23] New research indicates that there is not a trade-off between managing for productivity and carbon storage; stands managed with early (prior to onset of canopy closure and intense competition), pre-commercial thinning had lower densities, larger trees, greater structural complexity, and stored as much aboveground carbon as un-thinned stands (Schaedel et al. 2017).

KEY KNOWLEDGE GAPS

Many knowledge gaps still need to be filled to better understand and prepare Montana's forests to survive and thrive under a changing climate. We detail 12 key needs below to achieve better understanding of direct effects, indirect effects, and general effects.

- Better understanding of direct climate effects.—1) Improved understanding of adaptive genetic and phenotypic forest characteristics that would provide better guidance for breeding programs and management actions to maximize resilience to both direct and indirect climate impacts to forests; 2) Long-term studies to better understand effects of CO_2 fertilization in Montana's forests; 3) Improved models of climate and vegetation effects on evapotranspiration and water balances throughout forested systems.
- Better understanding of indirect climate effects.—4) Improved fire models and projections directly related to Montana's forests; 5) Long-term monitoring of forest insect and pathogen response to recent climate changes and improved projections of likely future impacts; 6) Better understanding of disturbance effects on microclimates and refugia and implications for forest productivity, mortality, and adaptation.
- Better understanding of general effects and adaptation options.—7) Forest models for Montana that account for changes in both climate and resulting vegetation distribution and patterns; 8) Models that account for interactions and feedbacks in climate-related impacts to forests (e.g., changes in mortality from both direct increases in warming and increased fire risk as a result of warming); 9) Systems thinking and modeling regarding climate effects on understory vegetation and interactions with forest trees; 10) Discussion of climate effects on urban forests and impacts to cityscapes and livability; 11) Monitoring and time-series data to inform adaptive management efforts (i.e., to determine outcome of a management action and, based on that outcome, chart future course of action); 12) Detailed decision support systems to provide guidance for managing for adaptation.

CONCLUSIONS

Much is known regarding how forest ecosystems will respond to climate change, even amid the uncertainties. Two conclusions can be made with high confidence:

- Rising temperatures and shifts in precipitation and moisture balance of forests are likely to increase negative direct effects on forests, particularly in water-limited systems and in years with low precipitation.
- In some regions, indirect effects of climate, due primarily to increased frequency and severity of wildfire and beetle outbreaks, will have a greater impact than direct climate effects.

By instituting adaptation and mitigation programs, forest managers can act now to lessen the likelihood and magnitude of climate change impacts on Montana's forests. Such programs, best undertaken in an adaptive management framework, include, but are not limited to, reducing fire risk; managing forest diseases; improving forest establishment; increasing forest carbon storage; improving water availability and soil quality; improving forest diversity, structure, and resilience; and increasing genetic and phenotypic diversity of forests.

Socio-cultural Concerns

*Sacred sites and traditional first foods.—Foods play a vital role in physical, mental, and spiritual health of indigenous communities. Many tribal communities rely on first foods for sustenance, and these foods are equally important to the sustenance of tribal culture. In Montana, examples of first foods and plants that are found in forests and open woodlands include camas (*Camassia quamash*), purple coneflower (*Echinacea angustifolia*), chokecherry (*Prunus virginiana*), red raspberry (*Rubus idaeus L.*), huckleberries (*Vaccinium spp.*), kinnick-kinnick (*Arcostaphylos uva-ursi*), wood's rose (*Rosa woodsii*), wild strawberry (*Fragaria virginiana*), arrowleaf balsamroot (*Balsamorhiza sagittata*), and fireweed (*Epilobium angustifolium*), in addition to deer, elk, and other game.*

*Climate change may reduce availability of these foods and plants, as well as shift gathering sites to locations not under tribal control (Voggesser et al. 2013). For example, Holden et al. (2012) showed huckleberry and serviceberry (*Amelanchier alnifolia*) productivity is sensitive to climate variation. Forest changes may also impact sacred sites. For example, some sacred sites are named after the long-standing vegetation communities grown in that area; yet many of the species may no longer be present under future climates.*

Native people have harvested camas (*Camassia quamash*) for millennia as a food source in Montana. Here, native youth dig for camas roots as part of the 2011 Northwest Montana Native Youth Conservation Corps. Courtesy of US Fish and Wildlife Service.

Timber production and wood industry.—Potential climate change-induced impacts to commercial forestry have been reviewed in several places (e.g., Kirilenko and Sedjo 2007; Vose et al. 2016; Keane et al. forthcoming), as has the status of Montana's forest products industry (e.g., McIver et al. 2013). In summary, potential increases in forest productivity from climate shifts (Lin et al. 2010; NPS 2010) could result in increased timber production in Montana (Garcia-Gonzalo et al. 2007). However, decreased vigor and increased mortality might offset gains in productivity from climate alone (Kirilenko and Sedjo 2007; Vose et al. 2016). Increased diseases, insects, and fires could also reduce quality of timber, thereby reducing the value (Spittlehouse and Stewart 2004; Kirilenko and Sedjo 2007; Gillette et al. 2014).

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Photograph courtesy of Scott Bischke.

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Sunrise along Montana's Hi-Line.
Photograph courtesy of Scott Bischke.

KEY SECTOR

05. AGRICULTURE AND CLIMATE CHANGE IN MONTANA

Bruce Maxwell, Becky Weed, Laura Ippolito, Anton Bekkerman, Madison Boone, Megan Mills-Novoa, David Weaver, Mary Burrows, and Laura Burkle

Montana agriculture has always faced variability and occasional extreme events. Wry commentary about the challenges of such variability might even be called a defining trait of rural culture in Montana. Characterizing the impacts of global climate change on Montana's diverse and historically variable agriculture is not clear cut. In the Third National Climate Assessment Melillo et al. (2014) described the challenge, though for the country as a whole, as follows:

KEY MESSAGES

- There are multiple drivers of decision-making in agriculture. Climate change is only one of the drivers motivating agricultural innovation, but it will become more important as warming continues into the future. *[high agreement, robust evidence]*

- Every component of agriculture—from prices to plant pollinators and crop pests—exhibits complex relationships to climate, depending on the location, weather variability, and agricultural and economic practices and policies. Social and economic resilience to withstand and adapt to variable conditions has always been a hallmark of Montana farmers' and livestock producers' strategies for coping with climate variability. *[high agreement, robust evidence]*

- Projected temperature and precipitation increases may be favorable in the short term for some Montana crops and forage production, but the effects of warming will become increasingly disruptive as they accelerate beyond adaptation thresholds. More frost-free days and longer growing seasons will potentially enable greater crop diversity. However, more 90°F+ (32°C+) days will also 1) increase evapotranspiration and water demand for most crops; 2) limit grain development from pollination to seed (i.e., grain fill); and 3) elevate heat stress on livestock. *[medium agreement, medium evidence]*

- Decreasing mountain snowpack will continue to lead to decreased streamflow and less reliable irrigation capacity during the late growing season. Reduced irrigation capacity will have the greatest impact on hay, sugar beet, malt barley, market garden, and potato production across the state. *[high agreement, robust evidence]*

- Climate change affects global-price-determined commodity agriculture differently than it affects non-commodity agriculture. Commodity crops, such as small grains, are more directly driven by global markets and agricultural subsidies, whereas non-commodity crops tend to be more directly tied to local or specialized non-local markets and local micro-climates. *[high agreement, medium evidence]*

- Diversified cropping systems, including rotation with pulse crops and innovations in tillage and cover-cropping, along with other measures to improve soil health, will continue to allow adaptation to climate change. *[medium agreement, low evidence]*

- Models predict native plains vegetation will increase but livestock forage quality will decrease. *[medium agreement, low evidence]*

- Increases in temperature will allow winter annual weeds, such as cheatgrass, to increase in distribution and frequency in winter wheat cropland and rangeland. Their spread will result in decreased crop yields and forage productivity, as well as increased rangeland wildfire frequency. *[high agreement, medium evidence]*

- Projected increases in winter temperature and spring precipitation are likely to increase current crop diseases and pests. For example, increased planting of winter wheat will be accompanied by increased crop pests, such as wheat stem sawfly, and the natural regulation of this pest by native parasitoids will likely decline. *[medium agreement, medium evidence]*

The cumulative effects of climate change will ultimately depend on changing global market conditions as well as responses to local climate stressors, including farmers adjusting planting patterns in response to altered crop yields and crop species, seed producers investing in drought-tolerant varieties, and nations restricting trade to protect food security. Adaptive actions in the areas of consumption, production, education, and research involve seizing opportunities to avoid economic damages and decline in food quality, minimize threats posed by climate stress, and in some cases increase profitability.

In other words, any effort at assessing climate impacts on agriculture faces multiple layers of uncertainty, including uncertainty that 1) accompanies all climate projections, 2) is specific to agricultural projections, and 3) is created by adaptive actions (human interventions) that can mask a direct climate impact signal.

Consequently, in the chapter that follows we emphasize and place higher confidence in projections that are consistent with current climate trends and supported by agricultural data. We must also acknowledge longer-term climate projections that may not yet be manifest as agricultural impacts. We first provide a summary of key climate projections relevant for Montana agriculture, followed by a brief overview of the uncertainties associated with identifying and predicting climate change effects. We next review the influence of climate change on Montana crops and livestock, and on the associated roles of pollinators, disease, pests, and weeds. We also report a number of human adaptations already underway that may increase resilience in the face of climate change. This combination of uncertain projections, local and global effects, and potential for human adaptation makes it difficult to attribute current, much less future, changes and trends in Montana agriculture solely to climate change. Accepting the reality of that uncertainty, we conclude the chapter by discussing future challenges for the agricultural sector related to climate change and the next steps for research and assessment.

BACKGROUND

Agriculture is a key industry in Montana, generating over $5.2 billion in 2014 through the sale of agricultural commodities (USDA-NASS 2015). Montana's large agricultural industry consists of both crops and livestock, as summarized by revenue in Table 5-1.

Agriculture plays a dominant role in the state's land use and its people's sense of place. Thus, even though more Montanans live in cities than on farms and ranches (USDA Census of Agriculture 2012), many of them think of Montana as an agricultural state, where the non-forested landscape is dominated by livestock and crop production.

Montana's farm and ranchland is a mosaic of dryland and irrigated agriculture, commodity and specialty cropland, and native and planted rangeland, all set on a backdrop of public and private lands that represent a spectrum from cities to wildlands. The analysis in this chapter separates Montana into seven agricultural regions (USDA-NASS 2015), which correspond to the seven NOAA-defined, Montana climate divisions in Figure 2-3 (Climate chapter). The seven agricultural regions are characterized as follows:

- Northwestern and southwestern.—The mountain valleys of the northwestern and southwestern regions are dominated by hay and livestock production with a few isolated areas of small grains, seed potatoes, malt barley, and other rotational crops. In addition, this region has irrigated, small-scale market garden and orchard crops surrounding urban centers and Flathead Lake.

Table 5-1. Summary of major crop and livestock revenues in Montana in 2015 (USDA-NASS 2015).[24]

Commodity	Value (US dollars)	National Rank	% US Total	Cropland Acres in MT Planted	Proportion of Total Cropland Acres in MT	Proportion of All Land in Farms and Ranches
Durum Wheat	$125,969,000	2	25.1	435,000	2.55%	0.73%
Other Spring Wheat	$634,144,000	2	17.5	3,050,000	17.91%	5.10%
Winter Wheat	$538,182,000	2	6.7	2,500,000	14.68%	4.18%
Barley	$238,038,000	2	25.3	920,000	5.40%	1.54%
Fruits, vegetables, melons, and tree nuts	$192,814,000	n/a	n/a	n/a	n/a	n/a
Lentils	$40,151,000	1	52.3	130,000	0.76%	0.22%
Dry Edible Peas	$99,792,000	1	52.9	525,000	3.08%	0.88%
Austrian Winter Peas	not available	2	31.1	12,000	0.07%	0.02%
Sugar beets	$49,250,000	5	4.6	45,100	0.26%	0.08%
Potatoes	$46,285,000	13	0.9	11,500	0.07%	0.02%
Corn (grain + silage)	$28,125,000	36	0.1	130,000	0.76%	0.22%
Oats	$3,643,000	17	1.6	45,000	0.26%	0.08%
All Hay	$668,427,000	8	3.9	2,730,000	16.03%	4.57%

Livestock	Gross Income (dollars)	National Rank	% US Total	Pasture and Range Acres in MT	Proportion of Total Pasture and Range Acres in MT	Proportion of All Land in Farms and Ranches
All cattle and calves	$2,014,017,000	11	2.8	n/a	n/a	n/a
Hogs and pigs	$78,612,000	23	0.3	n/a	n/a	n/a
Dairy products	$65,560,000	n/a	n/a	n/a	n/a	n/a
All sheep	$50,525,000	8	4.1	n/a	n/a	n/a
Honey	$29,225,000	4	8	n/a	n/a	n/a
Eggs	$12,966,000	35	0.1	n/a	n/a	n/a
Chickens	$3,100,000	35	0.1	n/a	n/a	n/a

[24] Appendix 5-1 on the MCA website expands on these data to show acres harvested, yield per acre, tons of production, and animal numbers for each of the seven agricultural regions (see below) in Montana.

- Central.—The southern portions of the central region are dominated by livestock and hay production. A large part of the area is irrigated, with some isolated small-grain production.

- North central.—The *Golden Triangle*, known primarily for its wheat production, represents a large part of the north central region. The region is dominated by dryland, small-grain production (with alternate fallow years to store soil moisture), with some legume and oil seed rotational crops. Livestock agriculture is less important than in other regions of the state.

- South central.—The west half of the south central region is dominated by livestock and associated irrigated hay production. The east half (Yellowstone, Big Horn, and Treasure counties) is characterized by river valleys with irrigated crops and by dryland winter wheat production.

- Northeastern.—The northeastern region is dominated by dryland small-grain production, including spring wheat with more continuous cropping by rotation with legume and oil seed crops. Livestock agriculture is less important than in other regions of the state.

- Southeastern.—The southeastern region includes extensive rangeland with cattle production, dryland winter wheat, and some rotation with oil seed crops. Row crops, including sugar beets, dominate the river valleys, with corn and soybean production increasing.

Agricultural irrigation is generally most extensive in the southwestern quadrant of the state, but there are pockets of irrigation dependence throughout Montana that do not correlate strictly with the regional divisions. The Water chapter of this document addresses climate impacts to water supply issues and more extensive documentation of agricultural irrigation in Montana is available in the 2015 Montana State Water Plan (MT DNRC 2015). The DNRC Plan includes maps and assessments of hydrologic basins and irrigation infrastructure, including context of climate projections. We do not reproduce those data on a region-by-region basis, but we do discuss the relationship between irrigated crops and climate change.

Stubble field near Rapelje.
Photograph courtesy of Scott Bischke.

SUMMARY OF KEY CLIMATE PROJECTIONS FOR MONTANA AGRICULTURE

As described in the Climate chapter of this assessment, average annual temperatures in Montana increased from 2.7°F (1.5°C) between 1950 and 2015, with even higher warming occurring in winter and spring (3.6°F [2.0°C] and 2.6°F [1.4°C], respectively). As a result, the annual growing season lengthened during roughly the same period by 12 days. Average annual precipitation for Montana, in contrast, did not change markedly between 1950 and 2015.

Climate model projections show a warmer Montana in the future, with mixed changes in precipitation, more extreme events, and mixed certainty on upcoming drought. As the basis for the chapter to follow, we provide summaries of the scaled-down global climate model projections for each of these climate variables below. More in-depth information can be found in the Climate chapter of this assessment.

- Temperature projections.—The state of Montana will continue to warm in all geographic locations, seasons, and under all modeled global emission scenarios, throughout the 21st century. By mid century and end-of-century, respectively, Montana temperatures are projected to increase by roughly 4.5-6.0°F (2.5-3.3°C) and 5.6-9.8°F (3.1-5.4°C), depending on emission scenarios. These projected temperature increases are larger than the average changes projected globally and nationally.
- Precipitation projections.—Across the state, precipitation (rain and snow) will increase in winter, spring, and fall. Precipitation is expected to decrease in summer. The largest increases are expected to occur during spring in the southern part of the state, with increases of 0.2-0.4 inches/month (0.5-1.0 cm/month) and 0.4 inches/month (1.0 cm/month) expected by mid and end-of-century, respectively, depending on emission scenarios. The largest decreases are expected to occur during summer in the central and southern parts of the state (0.2 inches/month [0.5 cm/month] by end-of-century under two emission scenarios).

Extreme events.—Agricultural productivity is highly vulnerable to extreme weather events, such as flooding, blizzards, hailstorms, and drought (Melillo et al. 2014). Although it is not possible to predict the precise location, magnitude and timing of such events in the future, more extreme events, as part of increased climate variability, may impact agricultural systems over and above those impacts associated with gradual climate change (Harrison et al. 2016). For example, crop-damaging hail events have consistently occurred in south central Montana in July from 1901-1980, with a slight increase in frequency from 1960-1980 (Changnon 1984). Recent predictions of hail threat over North America indicate that southwest and eastern Montana will see a significant increase in severe hail days in spring and early summer in 2041-2070 compared to 1971-2000 (Brimelow et al. 2017). Potentially damaging hail events for agriculture in Montana are generally predicted to increase if one assumes that hail larger than 0.4 inches (1 cm) in diameter is likely to damage crops or livestock (Figure 5-1). Brimelow et al. (2017) used dynamically downscaled data (on a 31-mile [50-km] grid) from the North American Regional Climate Change Assessment Program as input for HAILCAST—a computationally efficient, one-dimensional cloud model linked to a time-dependent hail growth model with microphysics to simulate the growth and melting of hail from first principles. Hail has its greatest impact on barley and wheat once heads with grain are formed (currently, early June for winter wheat and late June or early July for spring wheat and barley). Hail measuring 0.4 inches (1 cm) is enough to significantly damage small grain crops (Sanchez et al. 1996). The predicted increase (ΔGE1in Figure 5-1) of days of small grain damaging hail could result in increased hail damage insurance premiums, which further challenges the economics of Montana crop production.

- Drought.—Drought is more difficult to predict under a future with increasing greenhouse gas emissions. Drought seasonality, duration, frequency, and intensity all strongly impact agriculture—for example, reducing levels of soil moisture to support crop growth—and the lack of predictability under climate change is problematic. For Montana, increasing temperatures will likely intensify drought when it occurs, but precipitation projections do not reveal increasing duration or frequency of drought. When drought is discussed in the remainder of this chapter, it is referring to agricultural drought as defined in the Drought sidebar of the Climate chapter.

Projected Changes in Hail Events

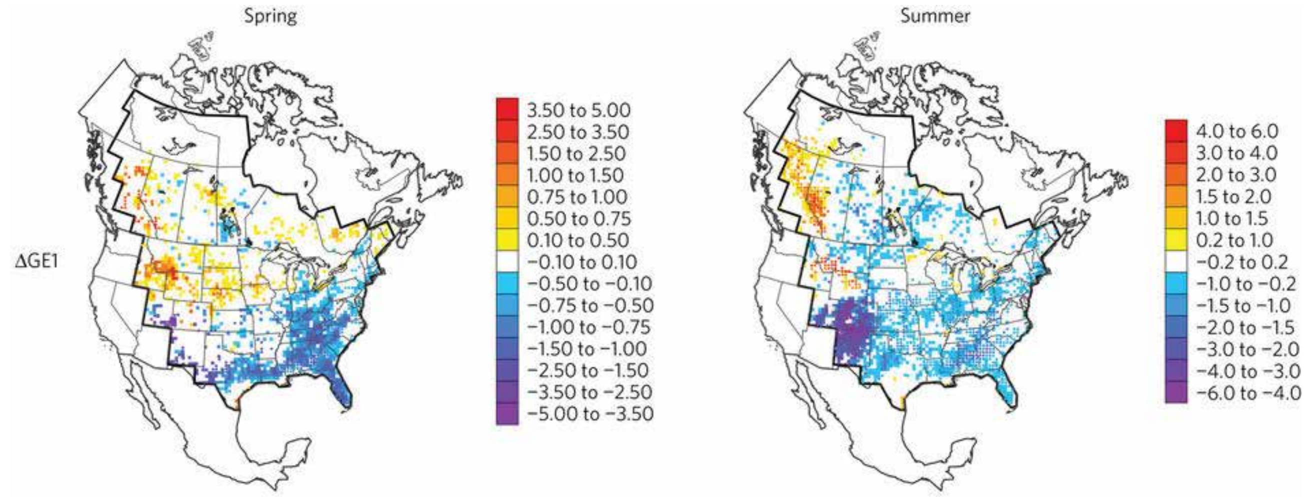


Figure 5-1. Mean changes in hail (diameter ≥ 1.0 cm) event days per season from the present (1971–2000) to the future (2041–2070) for spring (March-May) (left) and summer (June-August) (right) based on multiple model simulations. Colored cells indicate mean changes for all model pairings that agree on the direction of change; cells with colored circles indicate mean changes for at least two model pairings (Brimelow et al. 2017).

SOURCES OF UNCERTAINTY

Uncertainty accompanies efforts to assess the impacts of climate change on agriculture, including uncertainty in climate modeling (e.g., Melillo et al. 2014), in crop growth modeling (e.g., Ruane et al. 2016), in predicting livestock production, and in economic projections. Similarly, agricultural responses, largely driven by economics, may vary widely in the face of both local and global climate change. Such responses—also called *adaptive actions*—include altered planting and harvest dates, altered tillage and cover-cropping to manage water and weeds, adaptive grazing management, price support programs and other government subsidies, creation of specialized marketing channels, changes in crop selection, and crop insurance programs.

Climate change can affect all sectors of the agricultural industry, although in different ways at different scales, both directly and indirectly (Figure 5-2). For example, in considering agricultural markets: a) commodity grain revenues are affected by worldwide commodity yields and prices, which in turn might be impacted by global climate change; b) agricultural products marketed to consumers through local outlets (e.g., at farmers markets) can be affected by Montana's climate, and are less impacted by global price fluctuations; c) livestock revenues can be affected by climate through prices of input commodities or shifts in range availability or in markets; and d) sea level change may require relocation of port facilities that are critical to Montana grain exports and therefore could decrease price received or increase the cost of transportation, making grain farming less profitable and sustainable.

Interactions of Natural Systems and Human Interventions

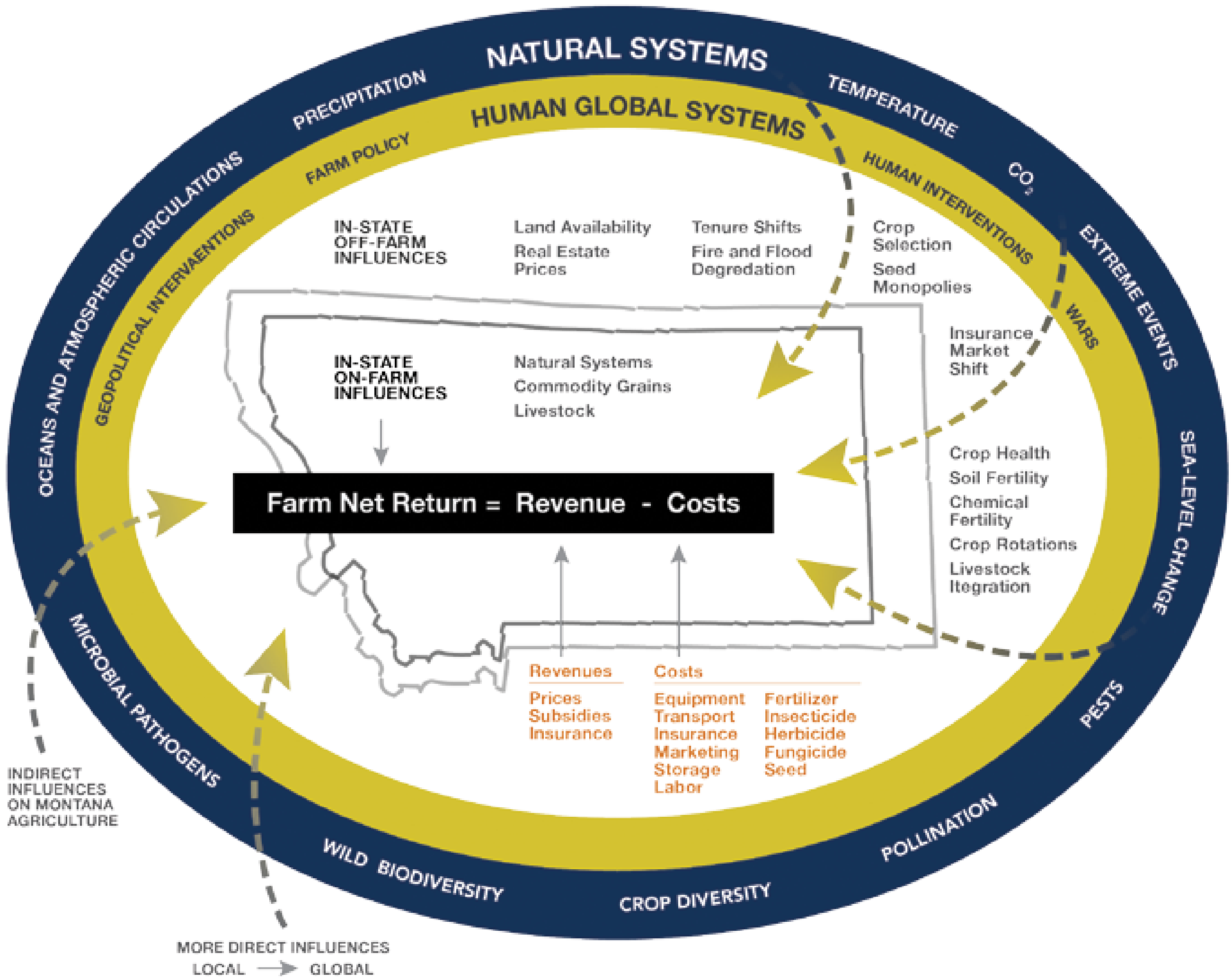


Figure 5-2. Interactions of natural systems and human interventions guarantee that climate change effects on agriculture, and vice versa, will be neither simple nor trivial.

Crop growth models are simulations that help estimate crop yield based on multiple projected growing conditions. While such models have not been run explicitly for Montana, they have been applied to other locations and can provide insights—though sometimes with conflicting results—for considering impact on Montana wheat. Highlights from those models include:

- In a European study on wheat, the ensemble crop model indicated that average yields would decline 3 to 7% per 1.8°F (1°C) increase in temperature (Pirttioja et al. 2015).
- Under projected climate conditions somewhat similar to Montana in Australia, dryland wheat yield loss was predicted to range from 24-94% by the 2060s depending on the site and the regional climate projection (Kouadio et al. 2015).

- Thirty different models for predicting global wheat grain yield indicated high levels of uncertainty when simulating crop responses to increasing temperatures. The research indicated that the median wheat grain production would fall 6% per 1.8°F (1°C) increase in temperature, plus become more variable over space and time (Asseng et al. 2015).

- Ruane et al. (2016) compared 27 wheat model global yield responses to interannual climate variability and concluded that there is only a weak relationship ($R^2 \leq 0.24$) between the model sensitivities to interannual temperature variability and the crops' actual response to long-term warming. This finding suggests that the models do not capture all the significant processes that affect wheat yield. Thus, the use of the physiologically-based crop-growth models to project climate responses may be highly uncertain without further refinements (Macadam et al. 2016).

- Results from a study of the Canadian prairie, the northernmost portion of the Great Plains of North America and adjacent to Montana grasslands, provide stark contrast to those described in the previous example (Smith et al. 2013). Researchers ran growth models using historical weather (1961–1990) and future climate scenarios (2040–2069; using IPCC Special Report on Emissions Scenarios). This study predicted that if no cultivar changes occurred, spring and winter wheat yields would increase by 37% and 70%, respectively. The indication is that northern regions are likely to see strong shifts toward increased agricultural productivity under climate change.

Results of these modeling studies, particularly from those from regions similar to Montana, are useful only with important caveats. For example, differences in temperature between Canada and Montana, and uncertainties in precipitation projections, influence crop model projections and call into question the ability to extrapolate the findings across major subregions within the Great Plains.

Even while the spectrum of modeling approaches used in these studies yield insights about variables that influence crop growth, it is apparent that absolute projections are not possible. Uncertainty exists for crop models, just as for climate models, and this must be acknowledged. Stakeholders of Montana agriculture may find the cumulative uncertainty of inexact crop models built on inexact climate models frustrating, but it is as important to understand the sources of uncertainty as it is to realize that temperatures are rising. Still, with temperatures rising and a strong need to understand the consequences for Montana agriculture, models provide our best tool for looking ahead. Models provide producers with a range of plausible scenarios to consider in designing adaptation strategies.

CLIMATE CHANGE EFFECTS ON COMMODITY CROPS IN MONTANA

Some of the crop production trends expected to accompany increasing temperatures are already apparent in statewide agricultural statistics compilations. The documented shifts *may* be attributable to climate change, but other factors may also contribute, in whole or in part. Due to the complex interplay of direct and indirect factors illustrated in Figure 5-2, the literature contains little documentation of climate change *alone* as being responsible for observed changes in Montana crop production.

As noted in the Key Climate Projections for Montana section (above), precipitation is projected to increase in some regions, and in some seasons, but not in others. This means that precipitation projections cannot be applied uniformly across the state, whereas temperature trends are more consistent statewide. Therefore, in this chapter we discuss observed and expected patterns of change for each of the major types of agricultural production rather than applying the climate trends equivalently across agricultural topics.

Shifting ratios of spring and winter wheat

Wheat is the number one commodity crop grown in Montana (Table 5-1). It has a production value of $939 million (USDA-NASS 2015), so changes in its acreage and distribution have significant implications for Montana's economy and agricultural practices.

A shift from spring wheat towards winter wheat production is expected, due largely to warmer winter temperatures that facilitate greater winter wheat survival, and warmer summer temperatures that impair spring wheat production by inhibiting seed formation, germination, and early growth (Lanning et al. 2010). The increasing proportion of Montana winter wheat since 2000 (Figure 5-3) *may* be attributable to climate change in particular because of a) more consistent autumn precipitation, b) warmer winters, and c) heat damage to later maturing spring wheat. This shift to winter wheat is expected to increase in the future as winter temperatures and summer days above 90°F (32°C) increase.

Proportion of Wheat Acres Planted to Winter Wheat in Montana

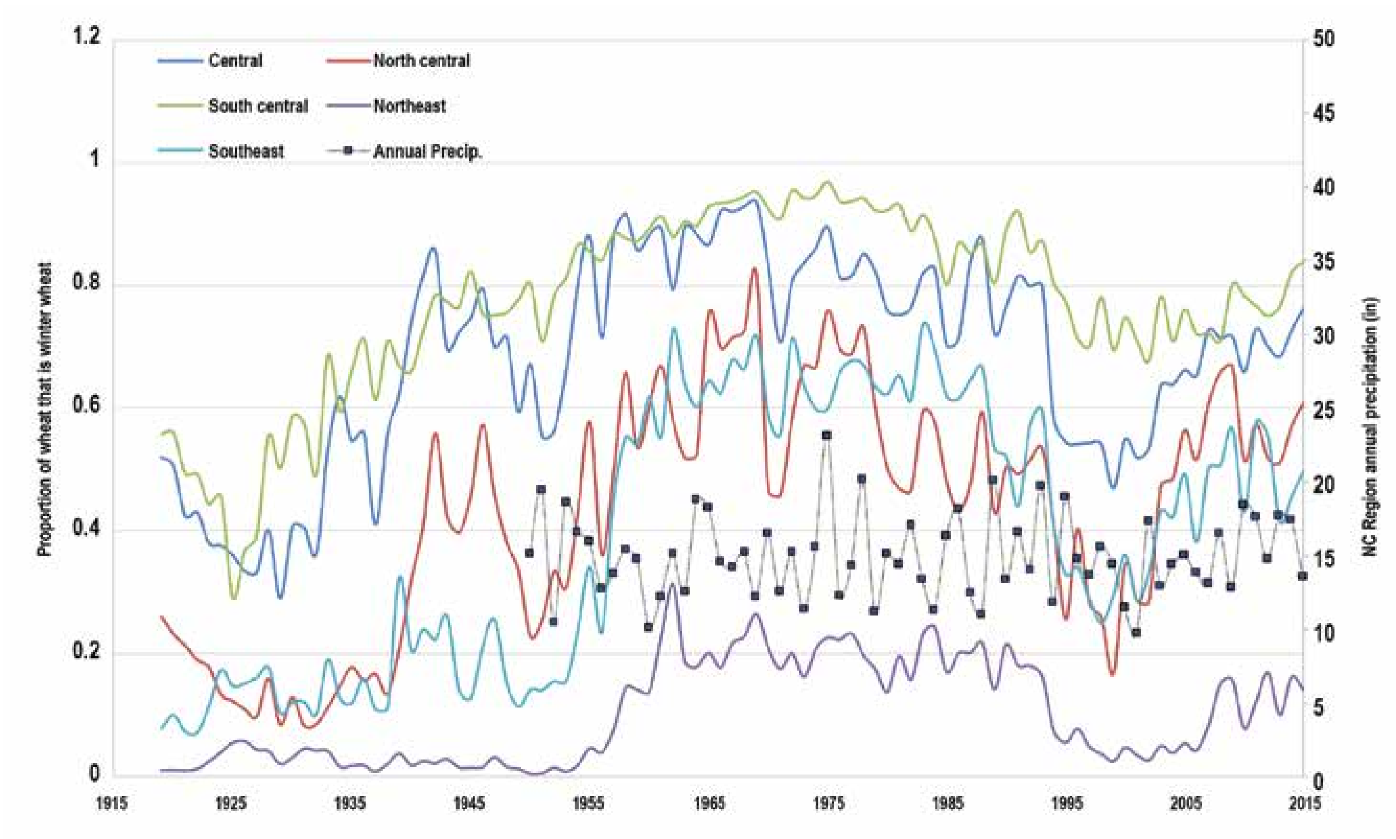


Figure 5-3. The proportion of total wheat acres planted each year in Montana as winter wheat (USDA-NASS 2015).

However, while such a shift has already been documented in some places (e.g., Prato and Qui 2013), many factors—including local or global price—can complicate crop preference shifts. Figure 5-3 shows two historical trends for winter wheat production that are most likely not attributable to climate change:

- The increase in winter wheat from 1925-1970 resulted from improved cultivars bred for Montana conditions, not climate change.
- The relative decline in winter wheat acreage from 1987-2000 was probably driven more by the Conservation Reserve Program (CRP) than by direct climate effects. The Conservation Reserve Program gave favorable rates to Montana producers, leading many to remove acres from wheat production and move them into CRP.

Importantly, the factors driving a farmer's choice to switch, for example, from wheat to a high-value rotational crop (e.g., lentils, corn) may change from year to year. Along with projected market price, farmers must balance these choices against myriad other considerations, including other crops and livestock on their land, government programs (e.g., CRP), labor scheduling, crop insurance, crop rotations, and family traditions.

Still, if current upward temperature trends continue or even accelerate, it is likely that the shift from spring wheat to winter wheat will continue. However, further analysis of crop selections and commodity pricing inside and outside Montana show, as discussed below, that projections regarding wheat cannot function in isolation.

Increased corn production

Corn acreage, and to a lesser degree soybean acreage, has increased across much of Montana since 1990, particularly in eastern Montana (Figure 5-4) (USDA-NASS 2015). Farmers can now grow corn in many areas where length of growing season, as well as spring and early fall temperatures, were formerly prohibitive. But in addition to the longer growing seasons, which may be driven by climate change (see Climate chapter), this improved feasibility of corn production in Montana is due in part to new, shorter-season corn varieties.

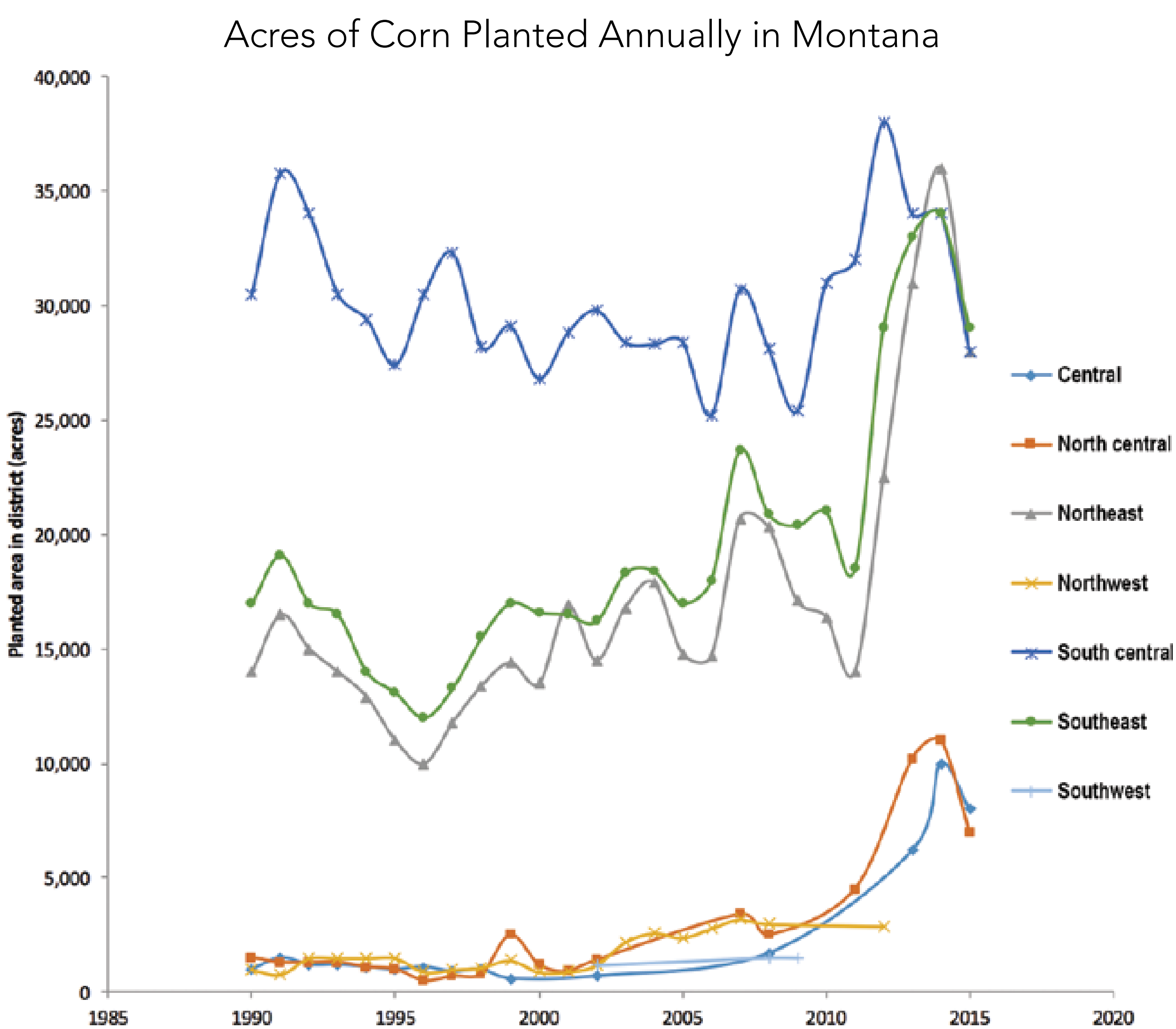


Figure 5-4. Acres of corn planted each year in Montana, including that grown for silage (USDA-NASS 2015).

Along with increasing temperatures and length of growing season, however, a combination of economic factors has favored the choice to plant corn in recent years:

- Profitability.—Corn has historically been more consistently profitable than many other crops, as indicated by comparisons of net return on labor and management in North Dakota (Aakre 2013; Newton and Kuethe 2015). This profit stability is due in large part to the major global market share that the US holds in corn production (40-45%). Therefore, US corn prices are not as sensitive to global conditions as wheat prices are. The US produces only about 7-9% of global wheat, causing wheat prices to be more dependent on what happens globally. Wheat price stability is also affected by discounts based on protein content, test weight, and weed seed dockage, whereas corn price is not so substantially affected by quality.
- Flexibility.—Farmers can harvest corn as silage for livestock feed, if necessary, even if the crop does not reach maturity. Thus, some Montana farmers are experimenting with corn acreage, even where there is still risk of early frosts terminating growth before maturity. Some Montana farmers may also be attracted to the option of using genetically modified, glyphosate-resistant corn to ease weed management, following a trend that has dominated agriculture in the midwestern US.

Whether this increasing corn acreage is being encouraged by warmer growing conditions caused by climate change, economic factors, or both, this expansion raises broader concerns about how crop selections will be made in a changing climate. Corn is an extremely water- and fossil-fuel-intensive crop typically grown as animal feed or biofuel, not as food for people. This allocation of resources is already the subject of debate with respect to midwestern corn, and there may be more pressure to adopt corn production in Montana with warming and increased precipitation as much of the continent becomes more arid. However, disease considerations may also play into crop selection trends, as wheat and barley growers are already raising concerns about corn as a disease carrier (see section on crop diseases).

Price volatility and the cost of uncertainty in commodity markets

The likelihood of increasingly volatile weather, both locally and globally, due to climate change will increase uncertainty in both local and global markets. In commodity markets, that uncertainty has a cost that relates not only to weather, but also to myriad choices involving forward contracting, futures marketing, crop selection, and crop quality.

Any agricultural decision has multiple drivers (Figure 5-5), but the discussion in this section applies specifically to the major commodity markets of Montana, where small grains, especially wheat, are dominant and pulses and corn are subsidiary. The most direct determinants of cropping decisions (i.e., crop selection) include input costs, pest conditions, government policies, and year-to-year price expectations.

Factors that Drive Agricultural Decisions in Montana

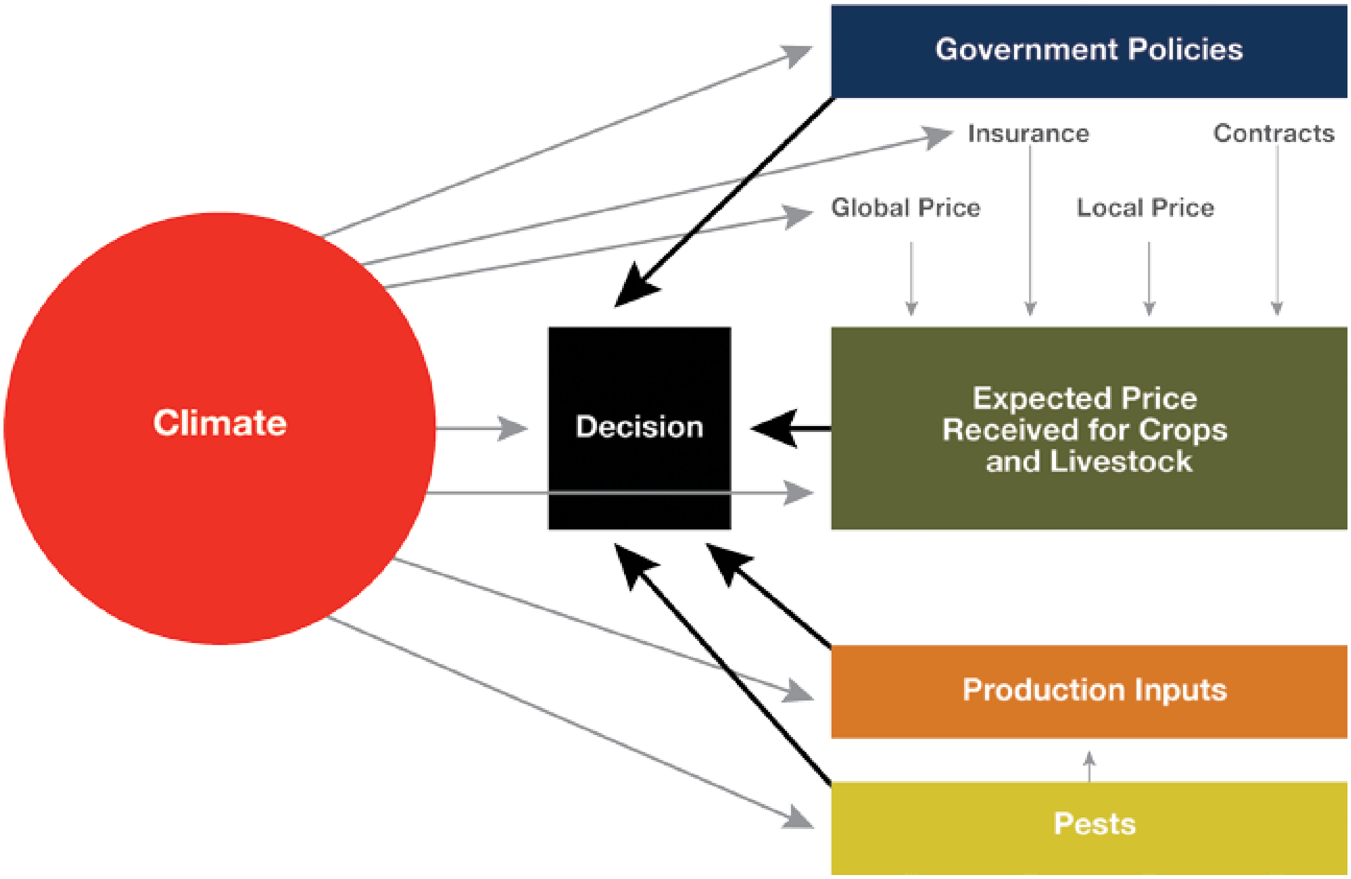


Figure 5-5. Factors that drive agricultural decisions in Montana. The size of bubble and arrows qualitatively represents the relative importance of each factor's influence on agricultural production decisions.

Near Ulm, Montana.
Photograph courtesy of Scott Bischke.

Climate interacts with all of these other variables shown in Figure 5-5, both directly and indirectly. Increasing uncertainty due to complex interactions, whether through volatility or new and hard-to-predict temperature and moisture trends, can disrupt agricultural decision-making and will probably become an even more important direct agriculture decision-driver in the years ahead. Climate change can impact the economics of Montana's commodity crop industry in three principal ways:

- Agricultural producers and grain handlers are likely to be exposed to greater market uncertainty because of climate change. That uncertainty, in turn, may be incorporated into an operation's cost structure, potentially leading to higher costs for both producers and marketers of the commodity.

- Climate change, and specifically rising temperatures, can alter Montana's ability to consistently produce high-quality, higher-protein spring wheat, a key market differentiator for the state. Such a change could reduce Montana's competitive advantage in global wheat markets and, as a result, reduce the economic returns from our state's agricultural sector.

- Changes to Montana's climate will likely alter the traditional selection of crops produced in the state. This change would alter Montana's role on the US and global crop marketing landscape, although whether these impacts will be positive or negative is uncertain.

The preceding sections of this document address climate impacts on wheat quality and crop selection (shifts to winter wheat or corn), but the economics of price uncertainty is also a consequence of climate uncertainty. The accompanying Basis and Climate Change sidebar introduces the concept of *basis*, an economist's tool for evaluating local and global influences on commodity prices; a more detailed analysis is provided in the appendices to this document.[25] For the overall purposes of this climate assessment there is a bottom line: if errors exist in basis forecast, the costs of forward contracting will increase beyond the "usual" risk premiums. Such errors could potentially result from economic models that fail to incorporate climate complexities, or do so poorly. In laymen's terms, price volatility builds upon the climate uncertainties of farming, and vice versa.

[25] Appendix 5-2 on the MCA website provides a more in-depth discussion of basis and its importance to Montana agriculture.

Basis and Climate Change

Basis is an agricultural economists' fundamental tool for understanding how markets incorporate new information into prices, including issues associated with climate change effects.

Basis (in $/bushel) = futures market price - local price *where*

- futures market price *reflects global conditions*
- local price *reflects Montana production conditions*

Basis can be used to assess differential impacts of climate change on local and global agricultural markets because it helps characterize how Montana-specific crop prices (reflective of local production conditions) are related to prices in futures markets (reflective of global conditions).

If climate change leads to basis becoming more negative (or less positive) relative to historical averages—that is, the local price decreases relative to the futures price—this would imply that the impacts of climate change likely affected local prices more adversely than global prices. Conversely, rising basis would mean that local production and marketing conditions were less adversely impacted by climate change relative to global conditions. Therefore, basis enables the analysis of wheat economics at a local level while accounting for global market conditions.

Pulse crops

Agricultural land planted with pulse crops (e.g., lentils, chickpeas, dry peas) has increased over the last 10-15 yr in Montana, with the northeastern region of the state leading the trend (Miller et al. 2002; Zentner et al. 2002; Cutforth et al. 2007; Burgess et al. 2012). Pulse crops provide multiple benefits to Montana farmers, benefits where management for climate change and management for other dimensions of farm health have the potential to converge. For example:

- Pulse crops enable farmers to diversify their production, thereby providing resilience in the face of climate change.—Diversification a) helps farmers cope with increasing climate-related variability in temperature and precipitation, and b) provides some insulation from price downturns on standard cash crops (e.g., wheat) (Miller et al. 2015).

- Pulse crop rotations can aid production of subsequent wheat crops.—Research shows that wheat crops benefit from a preceding legume pulse crop through the addition of soil organic matter leading to conservation of soil moisture and the addition of nitrogen (Miller et al 2002; Miller et al 2003; Cutforth et al 2007). Benefits, which improve resilience, include improvements in soil fertility and water-use efficiency, plus disruption of weed, pest, and disease life cycles. This finding has encouraged incorporation of pulse crops into rotations with wheat (Long et al. 2014), replacing summer fallow years. Miller et al. (2015) also show that in a wheat-pea cropping system, producers can reduce the amount of nitrogen that they apply, but in the long run maintain similar profits as a wheat-fallow system and reduce uncertainty around those profits.

Depending on the farmer's perspective, the increase in pulse crop acreage might reflect a response to observed climate change, an adaptation in anticipation of expected climate change, or simply a management change in the interest of soil health. To determine if climate change is playing a role in these crop selections, we compared the relationship between acres of lentils planted, prior-year price, and prior-year precipitation in north central and northeastern Montana (where prior-year precipitation represents a direct climate driver). When the regions were assessed independently, prior-year price appeared to be a strong predictor of crop selection whereas previous-year precipitation was not. This relationship suggests that variables other than Montana climate, such as market demand and/or climate forces outside Montana, may be more important in determining a farmer's decision to plant a specific crop. Agricultural traditions within each region may also influence crop-selection shifts.

Regardless of each farmer's reasons for adding pulse crops, this diversification provides benefits to soil health and helps build market resilience in the face of climate change (Zentner et al. 2002; Miller et al. 2015). Still, it should be recognized that pulse crops, like commodity grains, will experience a combination of climate change effects, some of which may counteract each other. For example, heat stress and pathogens may increase with a rise in temperatures, resulting in a decrease in production. However, more atmospheric CO_2 is predicted to increase crop biomass and subsequent yields, and reduce water use by allowing plant stomates to open over shorter periods, thus assimilating the same amount of atmospheric CO_2 while conserving moisture (Cutforth et al. 2007). To further complicate matters, grain protein can decrease under high CO_2, demanding increased nitrogen fertilizer to maintain quality (Kimball et al. 2001). Optimum crop selections and rotation planning are not trivial to optimize under such changing climate conditions.

Agronomists in the northern Great Plains have made significant progress over the last 15 yr encouraging the use of pulse crops, green manure, and cover crops to replace fallow land and reduce soil erosion (Miller et al. 2002; Tanaka et al. 2010; Nielsen et al. 2016). Studies show that soil moisture retention in most years did not significantly decrease with the presence of these crops (Miller et al. 2006; Miller and Holmes 2012), suggesting that this revenue-generating crop can replace a fallow year without incurring a moisture deficit. This beneficial opportunity, however, may not persist as evaporative and transpiration demands increase with projected warming temperatures under climate change.

The variable nature of climate change effects on pulse crops is leading to a variety of research approaches to enhance their versatility. For example, breeding varieties for early flowering and maturity takes advantage of earlier springs and avoids late-summer drought; and breeding to produce cold-tolerant pea and lentil varieties allows fall seeding. Fall seeding, in particular, enables improved seedling establishment when field conditions are warmer and drier, creates more balanced field labor requirements between fall and spring, and improves yield by avoiding high temperatures that quicken maturity (Chen et al. 2006; Cutforth et al. 2007).

Irrigation demand and supply

Irrigated agriculture in Montana involves a variety of crops (e.g., hay, grains, pasture, vegetables) in diverse settings, so generalizations about how a changing climate will affect demand are difficult. Furthermore, hay, pasture, and to a lesser degree grains are vital components of the livestock industry in Montana, so the implications of irrigation demand and supply extend well beyond crop yields alone. See the section of livestock for further discussion of these relationships. The Water chapter describes the basic hydrology of irrigation water supply, but superimposed on that are combined effects of increasing temperatures and dynamic cropping conditions. For example, longer growing seasons prolong water demand, and with earlier snowmelt and less water available late in the growing season, irrigated hay production is already, and will likely continue to be, constrained.

The difference between irrigated and non-irrigated hay production in tons/acre has increased over time since the 1960s (Figure 5-6). Since hay is made up of grasses and broadleaf species, comparing the production in water limited (non-irrigated) versus unlimited (irrigated) conditions is a way to estimate impacts of a warming climate on hay and forage production. The increasing rate of difference between irrigated and non-irrigated hay from northwest Montana to southeast Montana is correlated with a wet-to-dry gradient further suggesting a climate impact on productivity of animal forage. If one assumes water use efficiency to be constant over the mixed species hay crop, there is a climatic mechanism that explains the proportionally greater growth when the crop is irrigated:

increased transpiration demand on the non-irrigated plants resulting in decreased productivity. Increased water use efficiency with improved irrigation technology could confound these results, as could increased atmospheric CO_2 fertilization. However, there is little evidence that water use efficiency in hay production has increased significantly over time in the western US with improved irrigation technology (Schaible and Aillery 2012). The proportion of alfalfa in the total-hay-production statistic decreases from northwest to southeast Montana, which should increase the water use efficiency of the crop (Hendrickson et al. 2013). However, the opposite result appears to be the case, further implicating the role of climate or a climate/CO_2 interaction. The major concern with this trend is not just its impact on hay but also on rangeland native plant communities that are relied upon for livestock production for a large proportion of each year. Thus, to produce the same amount of hay in the future as today, Montana may increasingly seek to rely on irrigation. Yet at the same time less water may be available for irrigating hay given projections of reduced mountain snow pack (see Water chapter).

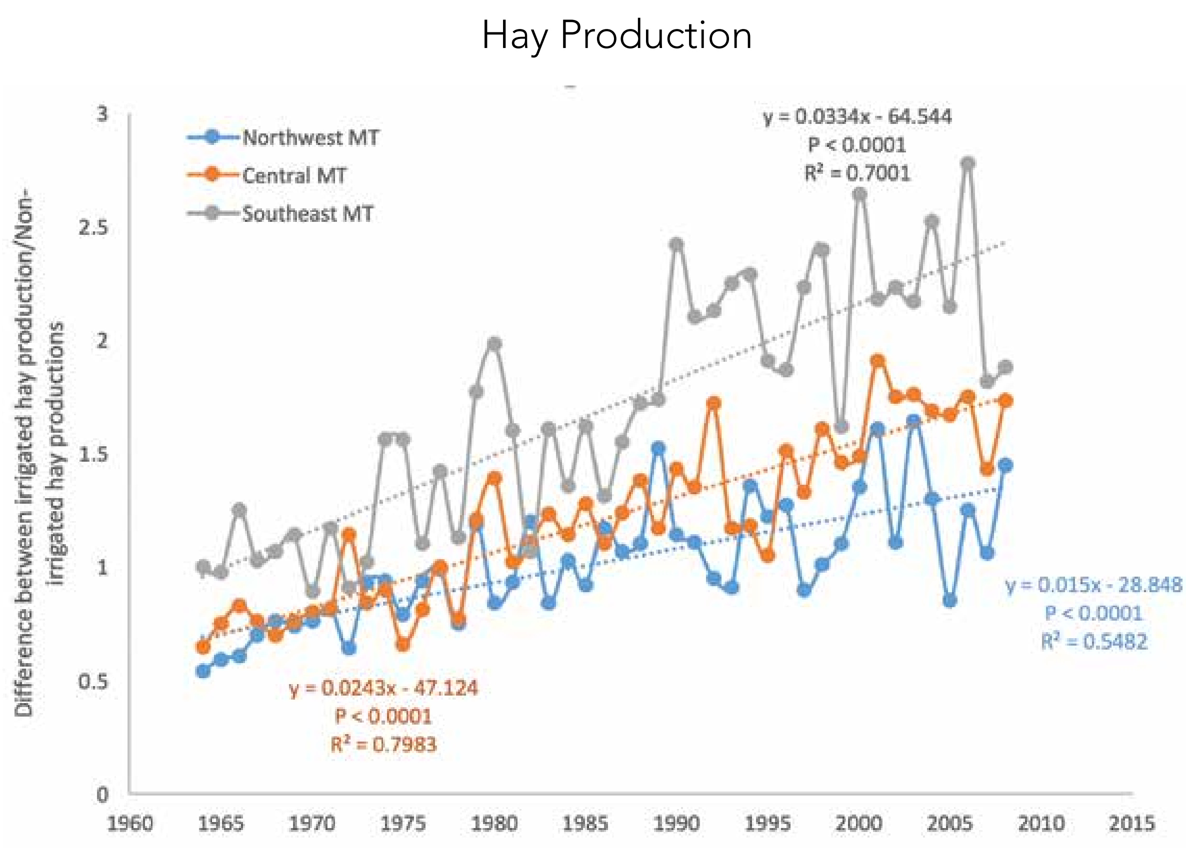


Figure 5-6. The difference between irrigated and non-irrigated hay production (i.e., irrigated hay production - non-irrigated hay production), which includes grass and alfalfa (USDA-NASS 2015).

Climate change is likely to exacerbate the relationship between increasing irrigation demand due to increasing temperatures and diminishing irrigation water supply from depleted groundwater and surface water storage (see Water chapter). Diminishing water supply will impact other crops beyond hay. For example, irrigated grain crops—including sugar beets, dry beans, potatoes, barley, wheat, and corn—will face analogous constraints of greater need for irrigation with less available water.

The capacity for farmers to modify crop selection and timing on an annual basis and respond to short-term weather fluctuations (year to year) makes it difficult to discern climate-change impacts in recent trends. But one thing is relatively certain: as climate changes and humans respond, the importance of irrigation to agriculture in Montana will not diminish (and, indeed, may grow).

Given the economic importance of highly developed crop irrigation districts in Montana and their susceptibility to climate change impacts, updates of infrastructure and careful management will be essential as impacts from changing climate become more pronounced with time. Such areas include the Bitterroot Valley, southern Flathead Valley, Beaverhead Valley, Fairfield Bench (Sun River Valley), Gallatin Valley, Musselshell Valley, Clarks Fork of the Yellowstone, the lower Yellowstone, and Milk River Valley. Most of these irrigation districts were constructed in the early 1900s and currently support high-value crop production, including market garden vegetables, alfalfa seed, malt barley, sugar beets, dry beans, potatoes, soybeans, corn, and hay.

Other large-scale production crops: sugar beets, potatoes, and organic grains

Sugar beets, seed potatoes, and organic grains are the three major crops grown by Montana farmers at substantial economic returns, but constitute much less acreage than the conventionally produced, major commodity small grains that dominate Montana farmland (e.g., wheat and barley; Table 5-1). Each of these three crops is economically significant in one or more agricultural regions within the state.

As with grains, no Montana-specific, peer-reviewed literature exists regarding climate change effects for any of these crops. For the crops under discussion in this section (and beyond), some climate changes may be favorable in the short term but may become increasingly disruptive as they persist and cross threshold levels. The exact timing and nature of these effects will vary, depending on such things as crop variety selection, farm microclimates, and market perturbations.

Sugar beets and potatoes.—

Researchers have studied the underlying climate controls for sugar beet and potato production over large regions (Tubiello et al. 2002; Jones et al. 2003; Haverkort and Verhagen 2008; Qi and Jaggard 2008). Although these studies do not apply specifically to Montana, they do illustrate several guiding principles that are useful in interpreting change and formulating expectations anywhere, including Montana. While crop growth models indicate that increased atmospheric CO_2 levels will increase crop growth potential, the accompanying suite of growth variables will play out differently in different locations given the changing temperatures and precipitation patterns expected (see Climate chapter). Based on the information in these studies, we might expect to see the following in Montana:

- In more northerly locations, such as Montana, longer frost-free seasons may assist growth, but increased volatility and extreme events may reduce yields.
- Increased precipitation can increase or decrease yields in certain seasons, but in some situations, increased fall rain may also hinder harvest and diminish the quality of sugar beets and potatoes.
- Timing and quantity of irrigation are particularly important for both sugar beets and potatoes, but requirements are not the same for both crops.
- As temperatures rise, Montana's seed potato industry, famed for low prevalence of disease, will likely face more disease pressure, particularly in areas where precipitation also increases.

The preceding list suggests that in the short term, sugar beet and potato production may face different responses to climate change, but in the long run water limitations due to rising temperatures and other climate-induced stresses could pose substantial challenges.

Organic grains.—Organic grains represent a small fraction (<1%) of the total acreage dedicated to conventional small grains, such as wheat and barley. Nevertheless, Montana produces more USDA-certified organic wheat—$27 million in 2015 (USDA-NASS 2015)—than any other state, and the acres planted with organic wheat continue to increase.

Organic grains are expected to be subject to many of the same climate-change challenges as small grains (discussed previously). However, the demand for organic products is less price sensitive than for conventional grains, and their production is not distributed globally as for conventional small grains (Bonti-Ankomah and Yiridoe 2006). They are marketed through a combination of direct and wholesale channels operating outside the mainstream grain transport and sales infrastructure. Many of the complications associated with price and input cost uncertainty in conventional agriculture are diminished or different for organic production.

Management for climate change and management for other dimensions of farm health are increasingly converging. Indeed, organic farming includes several practices that build resilience in ways that may be instructive for other sectors of Montana agriculture adapting to climate change. Such organic farming practices include a) prioritizing cover-cropping for soil health, moisture retention, and pest management; b) direct ties to food processing and retailing to reduce exposure to intermediaries; and c) increased emphasis on seed diversity. The issues embedded in seed diversity—that is the local adaptation and availability of diverse crop *varieties*—are important to the organic community and gain broader attention as plants become more stressed due to a changing climate. These practices are not new and were not initially driven by climate change, although the principles behind organic farming have always included promoting diversity and soil health. Many farms are increasingly incorporating organic farming practices that build resilience, regardless of their organic status. This trend will likely continue and help Montana adapt to climate change.

Specialty Crops.—Specialty crops are defined in law as "fruits and vegetables, tree nuts, dried fruits and horticulture and nursery crops, including floriculture" (USDA-NIFA undated). With the exception of tree nuts, Montana agriculture includes crops from each of these categories, although the acreage and revenues of specialty crops pale in comparison to those of commodity grains, livestock, sugar beets, and seed potatoes (Table 5-1). We focus here on fruit and vegetables, as food crops, although the principles likely apply to all specialty crops.

Longer periods of frost-free days and warmer temperatures overall improve growing conditions for most fruit and vegetable crops. Plant hardiness expectations, based on USDA data, suggest such changes may be underway in Montana, although it is not possible to identify farm-scale microclimate changes because the analysis is national and based on 30-yr temperature averages (NCA 2014b).

A 2015 USDA report (Brown et al. 2015) on how climate affects agriculture delineates the sensitivities of specialty crops to many climate components (e.g., temperatures, atmospheric CO_2 levels, water supply, cloud and light conditions, high winds and other extreme conditions). The report includes generalizations for annual versus perennial specialty crops and notes that specifics of management and microclimates will govern yields and profits. Some climate change effects will be beneficial for plant growth (e.g., elevated CO_2 concentrations and longer frost-free seasons), while others will be detrimental (e.g., plant damage due to extreme events, increased weed growth, new or expanded pests and diseases).

While fruit and vegetable agriculture is not a dominant sector in Montana, these crops are a key part of the Montana food market. They are typically more susceptible to erratic weather associated with climate change than are commodity crops. Small farm size, high per-acre crop values, and diverse marketing options can offer flexibility for specialty crops in many respects, but the challenges of perishability and intensive labor requirements counteract those benefits.

Fruits and vegetable crops are almost always dependent on irrigation in Montana. Paradoxically, this dependence is both a vulnerability and a strength. Dependence on irrigation represents risk. However, the use of drip-irrigation and intensive farming methods can enable small-scale food production where it is infeasible for more extensive commodity crops to adopt drip irrigation. Therefore, specialty crops represent a potential adaptation for farmers as climate changes. Climate changes outside Montana—particularly in California, where drought, fire, and competition with burgeoning human populations—threaten to limit national supplies of many fruits and vegetables. Such changes may amplify demand for Montana-grown crops.

CLIMATE CHANGE EFFECTS ON LIVESTOCK

Livestock production directly and indirectly relies on, and influences, virtually all other sectors of agriculture in Montana. The nature of the relationship varies geographically within the state, and sometimes varies within single counties and neighborhoods, depending on microclimates and cultural influences. Thus, the differential effects of climate on irrigated hay production, dryland hay production, native or non-native rangeland and pasture resources, and ultimately on feeds used for livestock finishing and backgrounding (grains, pastures and/or harvested forages) all play into livestock agriculture in different ways and at different times in the production cycle. Direct effects of climate on the animals themselves are also expected and discussed last in this section.

Forage and feed

To understand how climate plays out in the livestock industry and why climate signals are difficult to extract, it is necessary to recognize the industry structure in Montana. For cow-calf producers who rely substantially on irrigated hay production, irrigation supply issues may dominate climate change considerations, whereas for producers who rotate dryland hay with commodity crops, associated price/supply dynamics may predominate. On the other hand, for many producers grazing on non-cropped pasture and rangeland may largely govern the economics of feeder calf production. Many producers employ a composite of two or more of these feed sources (irrigated or dryland hay, crop residues, cover crops, rangelands), even adapting the relative importance of different feeds from year to year. Demand for Montana hay exports may also be driven by climate changes outside Montana (e.g., drought in southwestern states) and this can also reduce supplies in Montana. Other options for resilient management of ruminants under variable ranch conditions include grazing stockpiled forage, and/or swathed windows and bale-grazing, as well as the use of protein and energy supplements for winter feeding where forage quantity or quality is inadequate. All of these tools are already in use to varying degrees in the region and may become more widely practiced as conditions demand.

On top of this production mosaic, the methods, feed supplies, and marketing decisions used to bring meat animals to finish weight after initial calf or lamb production impose an additional suite of climate-dependent variables on livestock economics and ecology. The majority of commercial livestock producers in Montana market calves and lambs to buyers who will finish the animals (in and out of state) in grain- and/or forage-based feedlots. Other producers retain ownership during feedlot finishing, and still other producers are increasingly focused on grass-finishing of ruminants (i.e., cows, sheep, bison, goats) and direct sales. Although the grass-finishing sector is presently a small portion of the total livestock economy in Montana (and elsewhere), it is emerging as a focal topic in some circles as expectations of future climate change attract more attention. Commercial hog and poultry production, in contrast, are more exclusively dependent on feed grains. Dairies combine hay and grains for feed so their vulnerabilities to climate change are mixed. Hogs and poultry may be less vulnerable to climate change compared to ruminants as long as grain supplies are stable. However, they lack some options for flexible feeding that ruminants can exploit if grain supplies destabilize (e.g., adaptation to various forage types and locations).

Forage quantity and species distribution

Given the multi-layered structure of livestock production outlined above, efforts to analyze the influence of climate change on the forage end of the livestock cycle consider both species distribution and forage growth with respect to temperature, precipitation, and CO_2 concentration. The countervailing forces of rising temperatures (which may eventually lead to plant stresses) versus increases in CO_2 and/or precipitation (which enhance plant growth) will almost certainly alter forage productivity and community composition over time. Models predict that native vegetation production will increase (Morgan et al. 2011; Mueller et al. 2016) but forage quality will decrease (Milchunas et al. 2005). However, a range of experimental and modeling studies demonstrate that the net effects will vary depending on the particulars of local species composition, climate variables (including animal heat stress), and range or pasture management (Izaurralde 2011; Reeves et al. 2014; Mueller et al. 2016; Reeves and Bagne 2016).

The timing of precipitation is an especially important factor affecting forage plant growth and rangeland plant communities (Fay et al. 2002; Heitschmidt et al. 2005; Bates et al. 2006; Prevéy and Seastedt 2014; Hamilton et al. 2016). Late winter snows are the driver in one eastern Idaho location (e.g., Dagliesh et al. 2011), whereas April-to-June rains are key in a Montana rangeland site. Experimental work corroborates the importance of timing (Heitschmidt et al. 2005). Given projections of small but significant precipitation changes in some parts of the state (see Climate chapter), we can expect that forage patterns will be region- and season-specific. In the long-term, as rising temperatures increase evapotranspiration, heat stress may overtake temporary benefits of well-timed precipitation and CO_2 fertilization. The local details will matter in determining both the rate and severity of such forage losses, and we cannot generalize statewide.

In addition to the direct temperature/moisture considerations for rangelands and hay discussed above and in the crop subsection on irrigation demand and supply, three additional forage-related topics are connected to climate's influence on agriculture. These factors may increase in importance as climate change proceeds, as follows.

- Reductions in Conservation Reserve Program acreage increase livestock producers' vulnerability to climate-induced supply fluctuations.
- The increasing use of cover crops for various purposes (soil management, pollinator enhancement, other crop rotation goals) can also augment grazing opportunities for livestock producers. Although this currently represents only a small fraction of total grazing in Montana (USDA-FSA 2016), cover crop grazing may become an increasingly important tool for building resilience as climate change continues.
- Increased risk of grassland fire may intermittently threaten forage supplies in Montana, particularly where late season heat and aridity follow early spring rains that build up unusually ample grassland fuels. The vast fires that have recently afflicted portions of the southern Great Plains (spring 2017), demonstrate the potential for catastrophic events that may alter the economic conditions for affected ranchers for the foreseeable future. If such events persist and/or expand in the Great Plains, south or north, reverberations in the livestock industry may be profound.

Empirical data on forage quality

Climate change effects will simultaneously alter forage quality, along with quantity and species distribution, and these components affect animal nutrition. Craine (2010) acknowledges the difficulties of predicting forage quality shifts with climate change and takes a composite, empirical approach to evaluating cattle nutritional stress. The paper reports on decreases in crude protein and digestible organic matter over 14 yr, based on 21,000 cattle fecal samples across the US. By correlating these data with temperature and precipitation data associated with sampling locations, Craine (2010) infers that temperature increases will cause forage decline overall and that increased precipitation in some areas will be unlikely to compensate for declines in forage quality. On this basis, nutritional stress is likely to be seasonally focused in the form of mid-summer growth slumps, and/or late-season quality reduction in forages. Outcomes will depend on both local weather variability and forage management techniques (St-Pierre et al. 2003).

Implications for resilience

Forage studies and other research on tillage practices, moisture retention, carbon storage, and other climate parameters remind us that a climate assessment must acknowledge that not only does climate affect rangelands, but broad expanses of rangeland also may affect climate (Retallack 2013). Grasslands and their organic-rich soils can mitigate rising temperatures by serving as carbon reservoirs (e.g., Retallack 2013). Enhancing grassland production through active management, burning, and grazing rotations may become important parts of resilience strategies in the future.

The preceding discussion of the climate-forage connection is not comprehensive, but reflects a diversity of research approaches to detect climate change effects on livestock feed quality and quantity, as well as the shortage of Montana-specific publications. The grain component of livestock feeding programs is covered in the crops section of this chapter. The connections to irrigation practices and global grain supplies, to Conservation Reserve Program land, to cover-cropping practices, and to fire risks alluded to in this section and elsewhere in this assessment are all reminders that the interdependence of livestock and crop agriculture will likely loom large as Montana experiences the cumulative effects of climate change.

Heat stress

Examples of mechanisms and patterns, summarized below, help explain why there is such variability, and also reveal the avenues for building resilience in livestock operations to help mitigate animal stress. Heat stress affects ruminants through numerous physiological mechanisms (Nardone et al. 2010; Sevi and Caroprese 2012), and the timing, genetic make-up, and other variables determine the severity of the impacts (Bohmanoa et al. 2008; Bradshaw and Holzapfel 2008; Baumgard and Rhoads 2012). Relative humidity particularly influences the apparent or *felt* temperature, commonly expressed as the heat index, affecting livestock stress. Increased water vapor is expected to accompany increases in temperature (IPCC 2013), and as a result heat stress increases are compounded. In addition, heat impacts grazing animals differently than animals in confinement settings (Parsons et al. 2001; Turnpenny et al. 2001). Mu and McCarl (2011) predict that pasture use will increase relative to cropland based on modeling a combination of forage and animal response factors. Allred et al. (2013) suggest that native grazers may be better suited in the northern Great Plains than domestic cattle, citing different grazing behaviors in arid conditions.

Financial costs of heat stress are expected to increase in northern states, such as Montana, as summer temperatures rise. Based on comparisons with the southern US, where heat stress is already a significant cost estimated at a total of $2.4 billion annually for all livestock sectors (St-Pierre et al. 2003), we can infer that the costs of heat stress in Montana will become significant as the number of days above 90°F (32°C) increases. Despite consensus on these general points, an absence of specific projections once again characterizes the discussion, due to the complex mixture of microclimates, human agency, seasonality factors, genetics, and more. In addition, considerable evidence suggests that heritability indices are high and that genes for heat- and cold-tolerance are different. Thus, simultaneous selection for hot and cold conditions within breeds is potentially feasible in states like Montana (Howard et al. 2014), and discussion of these issues is already underway (e.g., Lemme et al. 2010).

Discussion of livestock feeding modes (grains versus forage) and animal management (intensive versus extensive) will arise as agriculture develops strategies for responding to a shifting climate. Ultimately, finding the optimal combinations of finishing methods for ruminant livestock (feedlot grains and/or forage strategies) will govern much of the economics and resilience of the livestock industry.

CLIMATE CHANGE EFFECTS ON POLLINATORS, DISEASE, PESTS, AND WEEDS

In this section, we look at potential climate change impacts on agriculturally significant pollinators, crop and animal diseases, and weeds and assess the implication of those effects for Montana agriculture.

Pollinators

The crucial role of pollinators (both commercial honeybees and wild pollinators) to agriculture, including in Montana, is undisputed. Researchers expect climate change to influence pollinators, primarily through elevated temperatures (Aizen et al. 2009).

No literature exists to describe climate change impacts on pollinators specifically in Montana. The majority of research on pollinators in agroecosystems has focused on such topics as habitat fragmentation, agrichemical use, and crop distribution, but less explicitly on climate change (Aizen et al. 2009). Efforts to examine long-term trends related to pollinators and associated with climate change are becoming more prevalent. Although that work has largely focused on *non*-agricultural systems, it is nonetheless instructive. Examples follow:

- In a warming climate, the timing of activity (i.e., phenology) of plants and pollinators is expected to shift, but these shifts may not be synchronized with one another (Burkle and Alarcon 2011; Burkle et al. 2013; Rafferty et al. 2013).

- Burkle and Runyon (2016) examine possible mechanisms underlying changes in pollinator behavior resulting from climate change and report that volatile organic compounds emitted by flowering plants are a primary pollinator attractant. Those floral volatiles may increase with drought, which is likely to be exacerbated, when and where it occurs, by climate change in Montana. However, prolonged water stress may in fact reduce production of floral volatiles, so climate effects on pollinators through that signal may be non-uniform.

- Focusing specifically on North American bumblebees, Burkle and Alarcón (2011) identify the main potential threats from climate change, including shifts in the timing of cues that initiate life history events, community interactions, and habitat growth. These threats could be applicable to other species.

- Otto et al. (2016) describe land-use changes (e.g., a major increase in acreage dedicated to corn and soybeans) in the northern Great Plains that are reducing suitable locations for honeybee colonies. Analogous crop shifts in Montana, potentially linked to climate change, could be similarly significant.

- Climate change is expected to influence the foraging activity, body size at maturity, and life span of wild pollinators (reviewed in Scaven and Rafferty 2013). Large-bodied pollinators are expected to be better able to thermoregulate (Bishop and Armbruster 1999) but are more likely to overheat than small-bodied pollinators (Heinrich 1993), which could influence foraging behaviors (Willmer 1983; Cooper et al. 1985). Warmer temperatures are expected to result in smaller adults with shorter lifespans (Bosch et al 2000; Bosch and Kemp 2003), which can influence pollinator effectiveness (Sahli and Connor 2007).

Montana is the second-largest honey-producing state in the US (USDA-NASS 2015). Each year beekeepers move Montana hives across the country to provide pollination services to other agricultural regions. Many Montana honeybee hives spend winter months in intensive agriculture regions (e.g., California almond orchards) before returning to a variety of forage-, prairie-, and grain-dominated landscapes in Montana. Thus, even if specific climate change effects on pollinators in Montana do materialize (or have already), they may be difficult to distinguish from non-local stressors.

The role of *native* pollinators in Montana agriculture is often underestimated. That role can be diverse and robust even as reports of commercial honeybee declines dominate headlines (Ollerton et al. 2012; Garibaldi et al. 2013; Rader et al. 2016). Like commercial honeybees, native pollinators are vulnerable to a variety of drivers, not just climate change. Thus, discerning a discrete climate-change signal is similarly challenging. Research may more readily detect climate-influenced patterns for native pollinators, however, since they are not transported around the country.

Wild pollinators by themselves can sufficiently pollinate certain crops (Kremen et al. 2002; Winfree et al. 2007), and wild pollinator diversity is the most important factor in stable pollination services to crops, regardless of whether honeybees are also present (Kremen et al. 2002; Klein 2009; Garibaldi et al. 2011; Rader et al. 2016). Thus, enhancement of native pollinator habitat (floral and nesting resources, natural or managed lands) represents an important avenue to support current and future pollination services in Montana agriculture (L. Burkle, Montana State University, personal communication, unreferenced). As the quality of some agricultural lands decline with climate change and more land comes under cultivation and development (Oleson and Bindi 2002), natural and semi-natural habitat will become more threatened. This potential situation only reinforces the importance of such enhancements for the maintenance of healthy wild pollinator communities (Garibaldi et al. 2011).

Crop diseases

Attributing fluctuations in crop disease directly to climate shifts is again uncertain and complex (Anderson et al. 2004; Garrett et al. 2011). A number of researchers have described plant disease expectations considering climate change variables, but without a Montana-specific focus (Canto et al. 2009; Chakraborty and Newton 2011; Garrett et al. 2011; Luck et al. 2011).

Still, we do have significant knowledge of the ecology of economically important crop diseases in Montana and we expect climate shifts will change crop disease impacts (e.g., yield losses, crop quality). Several examples follow:

- Stripe rust (*Puccinia striiformis* Westend), a wheat rust disease found in cooler environments, can lead to substantial yield loss. Farmers often apply preventative fungicide to susceptible wheat varieties, a cost that reduces net returns. Some strains of stripe rust are more aggressive at higher temperatures, some can survive winter conditions, and some can overcome the genes bred into the wheat to make it resistant to strip rust (i.e., termed a *resistance gene*). Thus, ongoing monitoring will be necessary.

- Wheat streak mosaic virus is a disease caused by a virus carried by the wheat curl mite (*Aceria tosichella*) and is widespread in north central Montana. Vector survival and reproduction of the virus increase when fall frosts are late and winters mild (thus causing greater impact). In addition, the genetic resistance that is currently present in some wheat varieties breaks down at high temperatures, thus eliminating that resistance strategy. Tillage practices, which can change soil moisture and temperature, may be necessary to reduce virus persistence and spread in no-till or low-till systems.

- Most foliar or leaf spot diseases (e.g., tan spot, septoria) are caused by fungi and will increase if farming practices tend toward more stubble on the ground, and moisture retention is enhanced as a strategy for coping with a warming climate.
- Insect and mite-vectored diseases, such as potato virus Y, barley yellow dwarf, wheat streak mosaic virus complex, and aphid-vectored pea viruses, may be enhanced if temperature changes lead to earlier migration or improved overwintering of vector populations of aphids.

Due to production goals, new crop varieties cannot always be substituted as a response to increased pathogens. The dominant approach for managing crop pathogens is instead, as in several examples above, breeding resistance into crops. One key question for Montana agriculture is this: Can crop breeding keep pace with changes in pathogen prevalence and migration resulting from climate change? Crop breeding alone may not meet the challenge; other tools, such as crop rotations and other measures typically associated with organic methods, may regain prominence as trends in the mean and extremes become more significant. Another key question is arising as some crop selections are shifting: do changes such as pulse crop expansion and/or increased corn acreage in some portions of the state expose the state's dominant wheat crop to new disease associations and dynamics (for example, fusarium in corn and/or viruses in pulses)?

Insect pests

Currently available data do not allow a comprehensive analysis of the likely impact of climate change on all commercially significant insect pests. We focus instead on one major insect pest—-wheat stem sawfly (*Cephus cinctus* Norton)—on Montana's dominant crop, wheat, to illustrate the mechanisms and principles involved in assessing climate change effects on agricultural pests and their impacts on crop yield or quality. This approach demonstrates that various factors can enhance or degrade a pest's impact on crops. Climate change impact analyses typically project increasing pest survival and crop damage with increasing temperatures (e.g., NCA 2014a), and wheat stem sawfly (WSS) may well be generally consistent with that pattern, but the following caveats help to show why generalizations across all landscapes in Montana, for all insect pests, are risky.

Several climate-related parameters—including indirect influences by crop, insect, and/or environmental traits—can collectively influence insect-pest outcomes. For example, in the case of WSS:

- Crop host.—Montana cropland has historically been dominated by a near monoculture of wheat associated with a large expanse of fallow land. In the last 10 yr, wheat acreage has averaged over approximately 5.6 million acres (2.25 million hectares). WSS (and some other pests such as orange wheat blossom midge) survive only on cereal crops such as wheat. Thus, WSS has become established in a wheat-dominated landscape, yet now that landscape has already begun to shift toward more diverse cropping, including pulses and oilseeds. That diversity may affect WSS-crop dynamics as crop diversification is expected to increase with climate change, but we cannot yet predict how much.

- Pest/parasitoid life cycle.—WSS is a native species that first adapted to spring cereals from grass hosts when crops were initially grown by western settlers (Anonymous 1946). Records show large increases in host range from grasses to spring to winter wheat (Anonymous 1946; Morrill and Kushnak 1996; Ivie 2001). This shift was accomplished by advancing the date of flight of WSS adults, successfully completing development in early maturing winter wheat crops. Currently, yield losses caused by WSS are greater in winter wheat than in spring wheat. Overall losses in wheat crops due to WSS will increase if climate change leads to more winter wheat acres. Compounding this effect, native killing agents of WSS (e.g., parasitoids *Bracon cephi* Gahan and B. *lissogaster* Muesebeck) have shorter life cycles than WSS, allowing for two generations per summer as opposed to the single generation of WSS. The first generation parasitoid attacks younger larvae of WSS and the second attacks the large larvae that are preparing to overwinter. However, the second-generation parasitoid cannot locate larvae if the crop ripens quickly and the larvae are no longer active and have already prepared to overwinter. This condition decreases the success of the second generation and reduces overall effectiveness of biological control on WSS. Surveys show a decline in proportion of second-generation parasitoids of WSS over the last decade (D. Weaver, Montana State University, personal communication, unreferenced).

- Timing of harvest.—Due to progressively earlier harvests and more rapid development of winter wheat crops, we expect that the success of the second generation of parasitoids will differ considerably for winter and spring wheat. Initial data are confirming this expectation (D. Weaver, Montana State University, personal communication, unreferenced).

- Resilience declines/feedback loops.—The decrease in overwintering parasitoids (D. Weaver, Montana State University, personal communication, unreferenced) is a significant concern, because the resilience of the parasitoid population might become exclusively dependent on later maturing grasses on the periphery of wheat fields. These grasses might allow the parasitoids to persist, but at insufficient population levels to continue significant mitigation of WSS.[26]

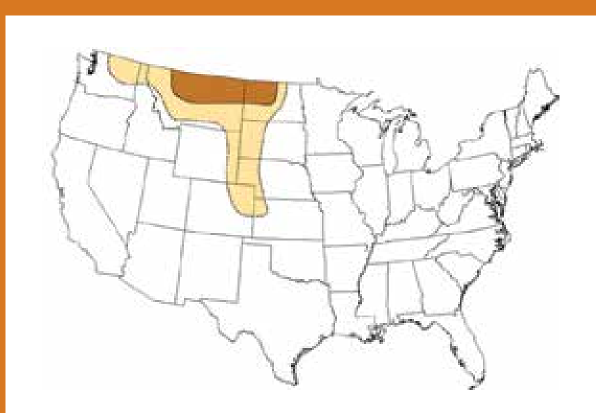
[26] For more detail on the impact of WSS, see Appendix 5-3 on the MCA website.

Although the particulars of host, insect, and ecological setting demonstrate the hazards of detailed projections, they also reveal plausible avenues for building resilience to help withstand climate change. Strategies, such as increasing crop diversity and rotations, retaining grass habitat strips to enable survival of beneficial parasitoids, and further exploring the survival dynamics of WSS and other pests, offer a range of opportunities for reducing vulnerability to pests. The WSS example (also see sidebar) shows that searching solely for simple relationships between temperature and pest survival may be fraught with uncertainty, not only for projection purposes but for adaptation and mitigation design as well. The details of pest/host dynamics clearly matter for WSS, and it is prudent to expect that they matter for other pests, as well.

The Wheat Stem Sawfly and Climate Change

*Crop injury due to the wheat stem sawfly (*Cephus cinctus *Norton) was reported, anecdotally, in 1910 from wheat fields near Bainville Montana (Anonymous 1946). The earliest pest records for this species in Montana are from spring wheat only (Ivie 2001). Since the late 1970s, however, the native wheat stem sawfly has used both spring and winter wheat as hosts (Morrill and Kushnak 1996; Lesieur et al. forthcoming).*

With the addition of winter wheat as a suitable host, the population dynamics of the wheat stem sawfly have changed. Morrill and Kushnak (1996) estimated that adults emerge from overwintering wheat residue approximately 20 days earlier than historical populations. This increasing suitability of winter wheat for the full wheat stem sawfly life cycle, because of the changing growing season, together with increasing winter wheat acreage, effectively doubles the acreage of wheat that can be damaged by the wheat stem sawfly.



Historical (dark shading) and recent (light shading) distribution of WSS in wheat crops in the northern Great Plains of the US. *Historical* means from first record through 2005, while recent is after 2005 (Bekkerman and Weaver forthcoming).

Infectious disease in animals

Most analyses of expected effects of climate change in agriculture include changes in disease dynamics (Plowright et al. 2012), but Montana-specific data are rare. As discussed throughout this assessment, the interplay of many variables complicates differentiation of the effects of climate change from other driving factors. Still, some recent outbreaks of livestock/wildlife disease in Montana have invited speculation about climate's role, although without definitive conclusions regarding causation.

Plowright et al. (2012) explain numerous mechanisms of disease transmission and how they will interact with different species and in different locations. The mechanisms of transmission are influenced by a suite of climate variables, metapopulation structures, and population densities and connectivity. The authors further dissect disease dynamics in terms of host behaviors, parasite life cycles, other seasonal attributes of disease transmission, and stress-mediated susceptibility.

Plowright et al. (2012) describe two examples that help explain climate linkages to numerous ecological attributes directly relevant to Montana agriculture:

- Brucellosis transmission.—Brucellosis transmission among elk near Yellowstone National Park is a function of snowpack (affecting elk herding), as well as duration and seasonality of aggregation (affecting overlap with abortion events). Potential transmission from elk to cattle similarly depends on seasonal circumstances, although human management (e.g., movement or segregation of cattle) may mask climate-associated effects.
- Parasite susceptibility in sheep.—For sheep on St. Kilda, an island in the North Atlantic, increasing temperatures has increased primary productivity. That increased productivity, in turn has led to improved body condition possibly enhancing the sheep's ability to withstand parasites. Parasitism in Montana sheep flocks may increase in response to elevated temperatures in some seasons and some locations, but the opposite could also occur, as shown in the St. Kilda example.

Weeds and invasive plants

Climate change is likely to impact plant distribution in the northern Great Plains and Rocky Mountain regions (Battisti and Naylor 2008), including that of weeds and invasives. We use the term *weeds* to refer to plant species that impact crops and separate the designation from *invasive plants*, which may have or have the potential to impact a broader array of agricultural activities on rangeland and pastureland. Increased expenditures for weed and invasive plant management in response to climate change could have significant economic impact on agriculture (Pejchar and Mooney 2009).

Studies show that increased atmospheric CO_2 concentration can drive increased weed growth and reproduction, although precipitation is an important mechanism mediating rangeland plant community response (Weltzin et al. 2003; Ziska et al. 2005; Mueller et al. 2016). Independent of precipitation, the combined effects of atmospheric CO_2 concentration and warming increased C3 rangeland grass productivity over time in a controlled experiment in Colorado (Mueller et al. 2016). Conversely, others note that increased temperatures can result in negative impacts to weeds due to increased evaporative demand (Larson 2016). Additionally, Hellman et al. (2008) note that climate change will likely impact weeds and invasive species by altering their transport and introduction mechanisms, establishment, ecological impact, and distribution, as well as the effectiveness of control strategies.

Under rapid climate change, weeds and invasive plants may have an advantage over desired and native plants because many have evolved to excel at dispersal, establishment, and adapting to new and changing environments (Corlett and Westcott 2013). Still, even an obvious regional shift in a weed species can be difficult to attribute to climate change. For example, jointed goatgrass (*Aegilops cylindrical*), a major weed in winter wheat, has steadily moved north in the Great Plains (Anderson et al. 2004). That movement might be explained by greater warming in the north. Alternatively, it might be a result of patterns of winter wheat harvest, which moves from south to north and has been a major vector of seed dispersal through passive transport on harvest equipment (Petit et al. 2013).

Impacts of increasing temperatures.—Winter hardiness zones are predicted to move north (Parker and Abatzoglou 2016), and elevational boundaries are likely to increase, based on increasing temperature projections (see Climate chapter).

With increased winter temperatures, weeds with a winter annual life cycle (i.e., plants that germinate in autumn and mature in spring or summer of the following calendar year) are likely to exhibit higher winter survival rates. This positive impact on survival rate will result in ranges expanding to the north and to higher elevation (Bradley et al. 2016). The indirect effects of increased fire frequency may also be important for weeds with winter life cycles, because of their ability to rapidly establish on burned landscapes (Bradley et al. 2010; Taylor et al. 2014).

Summer temperatures in Montana are also projected to increase with notable increases in the number of summer days above 90°F (32°C) throughout the 21st century (see Climate chapter). The increase in summer temperatures can contribute to increased wildfire frequency and intensity by drying fuels (Westerling et al. 2011), resulting in increased habitat for invasive species on rangeland (Alba et al. 2015). In addition, extreme heat during grain filling (i.e., the period of wheat development from pollination to seed production) can reduce crop yield (Lanning et al. 2010), thereby adding to the stress exerted by weeds. Those weeds, in turn, are more likely to be adapted to extreme heat.

Impacts of increased atmospheric CO_2.—Elevated atmospheric CO_2 generally increases plant water-use efficiency more for C3 than C4 plants. Those added efficiencies can translate to increases in biomass accumulation and reproduction, which can favor weeds over crops and invasive species over native forage species (Weltzin et al. 2003). For example, CO_2 enrichment has been shown to enhance the growth of downy brome (*Bromus tectorum*) in low-elevation desert and shrubland sites (Ziska et al. 2005). If Montana climate shifts to be more like that of the Great Basin (warmer and drier than current conditions), we might expect environments to increasingly be more compatible for *Bromus tectorum* (see sidebar).

Projections of Weed Expansion with Climate Change

*A prime example of a weedy plant predicted to increase in the northern Great Plains and Rocky Mountains is non-native downy brome (*Bromus tectorum*). It establishes rapidly on disturbed soils and is a dominant weed species in crop and rangeland (Bradley 2009; West et al. 2015; Bradley et al. 2016). Chambers et al. (2007) predict that the high flammability of this winter annual weed will increase wildfire frequency and thereby transform large areas of sagebrush steppe from perennial shrub to annual grass dominance decreasing the land's forage utility. Other studies suggest that its expansion into the northern Great Plains or Rocky Mountains will depend on rates of warming and drying (Taylor K et al. 2014; Larson 2016).*

*Similarly, Bradley et al. (2009) predict that yellow starthistle (*Centauria solstitialis*) and salt cedar (*Tamarix ramosissima*) will expand their range, downy brome (cheatgrass) and spotted knapweed will shift in range (neither increase nor decrease), and the range distribution of leafy spurge is likely to contract under predicted climate scenarios. Clearly, weed responses will be highly variable, even when similar driver variables are at play.*

Non-native downy brome (*Bromus tectorum*).

The impacts of climate change, whether direct or indirect, will present a significant challenge for weed and invasive plant managers in the future. Management will need to change—most likely to become more adaptive—under climate change (Prato 2008). Two examples follow.

- Impacts to herbicides.—Increased atmospheric CO_2 concentration will likely decrease the effectiveness of some herbicides important for maintenance of chemical-fallow between cropped years (Ziska et al. 1999; 2004; Wolfe et al. 2008).
- Impacts to biocontrols.—Climate change may alter the effectiveness of biocontrol agents, which is the use of natural enemies to reduce invasive species populations and a popular means of invasive species management on Montana rangeland. Negative impacts from climate change could include mismatches in the life cycles between the biocontrol agent and the targeted species (van Asch and Visser 2007), unexpected disruptions in host food webs, or shifts in host selection, all of which would diminish the efficacy of biocontrol agents (Pearson and Callaway 2003). Alternatively, the impacts of climate change may be positive, for example, by improving over-winter survival of the biocontrol agent, increasing its geographic range, or improving life-cycle match between agent and weed (Hellman et al. 2008).

THE FUTURE OF MONTANA AGRICULTURE

This assessment of climate change effects on Montana agriculture must start with the basic observations that temperatures are rising and precipitation trends are variable across seasons and regions in Montana. However, the joint importance of the natural environment and human and cultural market processes creates multiple layers of uncertainty and interactions that complicate identifying the effects of climate change. Observers both on and off the farm and ranch are recognizing the effects of climate change, even when market intricacies and changeable cropping practices seem intertwined. Longer growing seasons, less irrigation water, earlier grain harvests, lilacs in the farmyard blooming ahead of "normal," and hayfields that "don't produce like they used to," are conveying a consistent long-term message, even when prices, net revenues, and other measures of the farm economy are variable. When we combine the on-farm observations with others beyond the farm gate, like northward-moving ranges of songbird species and shifts in important pollinators, a pattern begins to emerge that is steadier than commodity prices (Chen et al. 2011).

Beyond providing some of the direct climate-driven responses to crops and livestock, a climate assessment for agriculture must also point out the likelihood of some seemingly contradictory expectations. In the short term, some regions of Montana may experience combinations of increased precipitation and milder temperatures and/or longer growing seasons that can lead to both positive and negative on-farm outcomes. For example, atypical early fall rains improve fall grazing and infiltration of soil moisture before frost limits infiltration, but these same rains can impair some grain harvests and/or fall plantings. Pest problems may increase in some regions due to increasing humidity and warmer conditions, but elsewhere some disease issues will likely initially diminish as aridity increases. Thus, the impacts of climate change for agriculture will almost certainly be highly variable, including at the local scale that is of most interest to farmers and ranchers.

In the short *and* long term, Montana agriculture may experience as much or more impact from climate change outside Montana as it does from direct, in-state effects. This potential exists primarily because commodity markets for grains and livestock have profound effects on markets for Montana's farms and ranches. This phenomenon is already underway and is likely to increase in significance. For example, drought in India has helped build markets for pulse crops like lentils and dry peas in Montana. In more complex scenarios, climate change effects across the globe can lead to geopolitical disruptions that also alter wheat and beef markets in positive or negative ways for Montana agriculture revenues. This susceptibility to global affairs is not new to Montana agriculture, but climate change will likely amplify uncertainty for producers.

In the long term, the dominant implication of climate projections for agriculture is that change will not remain gradual. The masked and messy shifts that are underway may reach tipping points that enable and/or force rapid, transformational change in our food systems. Many of the crop, livestock, market, and ecological changes referenced in this chapter have been buffered by many things: surplus harvests, crop insurance, disaster assistance, off-farm income, on-farm ingenuity, market flexibility, and the intrinsic resilience of our landscapes. Furthermore, consumer and taxpayer capacity to bolster that buffering capacity, through food prices and taxes to cover agricultural subsidies, is finite. Because of the sources of uncertainty, many described in this assessment, we are not currently very good at projecting the exact timing of such disruptions. The familiar mantra "more research is needed" is almost always valid, but also, in the face of climate change, insufficient and likely tardy. Region-specific climate projections, historical data on crop production, and more extensive analysis of crop responses will improve our understanding of future patterns, but uncertainty will persist.

KEY KNOWLEDGE GAPS

Emerging questions about building an adaptive and resilient agriculture involves several lines of inquiry. It is clear that climate change will influence agricultural decision-making in different ways, and the more we focus on local adaptive practices the higher the likelihood of success. Whether one seeks to tweak existing systems or more radically overhaul them over time, the following questions are relevant for the future:

- Precipitation.—With the high certainty of warming and the lower certainty of future trends in precipitation, how do we develop resilient agricultural practices that prepare for divergent futures?
- Crop and livestock models.—a) How can crop and forage production models linked with climate models provide useful projections to inform agricultural decisions? b) Which models best inform management of livestock under predicted new climates? c) What mechanisms for data acquisition and accessibility allow appropriate climate and production model parameterization?
- Water.—a) When and where will irrigation be most disrupted as temperatures rise and water storage declines? b) How can we modify our methods for water retention, allocation, and efficiency to increase crop and livestock resilience to climate variability?
- Soil carbon.—a) In which systems and regions can improving soil organic matter help build resilience under volatile climate conditions, including severe drought? b) How can grassland protection and restoration help increase resilience to climate changes, as well as be integrated into food production? c) Which agricultural practices will build soil carbon reserves and serve as viable greenhouse gas mitigation strategies?
- Input practices.—a) Can inputs continue to be used as insurance to protect against variation? b) Does dependence on inputs contribute to creating less resilient agricultural systems? c) Can some inputs increase resilience?
- Commodity markets.—a) How can increased value-added production practices reduce dependence on volatile commodity pricing and thereby build resilience? b) When and where do traditional methods for farmer and consumer protection (e.g., crop insurance, government reserves) need revision to more effectively respond to climate-change uncertainty? c) How can revision of commodity market practices and expectations help develop resilience in anticipation of climate-change induced volatility? d) What improvements in enterprise-level financial and risk management strategies are needed to better manage market and production risks?
- Crop and livestock diversity.—a) How can introduction of diversity to cropping and livestock selections and systems help build resilience to climate change?

b) In which current homogeneous production systems can diversity be reintroduced without economic loss? c) How may increased agricultural diversity impact quantity and quality of goods produced in agriculture?

- Policy.—a) Which state and national policies influence producer's ability to adopt practices more resilient to climate change? b) What role can Montana seed providers, food processors and distributors play to increase agricultural resilience in the face of the uncertainty presented by climate change?
- Rural Sustainability.—a) How will agricultural communities be maintained and need to change in response to climate change? b) How will decisions at all spatial and temporal scales need to change to increase resilience to climate change?

NEXT STEPS

This assessment of the potential impacts of climate change on Montana agriculture is a starting point to identify and prioritize the aspects of agriculture that might be most impacted. In many cases, there are already signs of significant response. To develop effective adaptation strategies for agriculture, we must understand the local trends in our agroecosystems. Monitoring the local climate and agricultural responses to climate change is a critical first step in creating meaningful knowledge on which to base management decisions. Localized management decision tools that increase our ability to estimate the impact of different climate scenarios in the face of all the other uncertainties are needed for decision-making. Successful development of these tools should not be limited to research by scientists. An all-hands approach will be necessary to address the interdisciplinary and site-specific implications of the interacting climate change effects that have been touched on in this chapter.

Building resilience to climate change in Montana's agricultural sector is paramount. Three premises underlie our ability to increase agricultural resilience:

1. Montana agriculture has always included, and will probably continue to include, a spectrum of approaches within any given system (e.g., cattle production, grain production, market garden vegetable production), but the relative economic importance of the approaches may change (e.g., global versus local marketing, cropping versus livestock, organic versus conventional). We need to be able to understand the economic and environmental impacts of those changes.
2. Defining success for agriculture in the future will entail matters of marketing, food supply, and food quality and access, as well as environmental health and farm net income. Therefore, understanding how these factors interact at different scales in space and time will be essential to maintaining sustainable agriculture.
3. Change is inevitable.

CONCLUSIONS

An assessment of climate effects on Montana agriculture is complex because of uncertainties inherent in the timing and manifestation of climate change, and because of complexity in how natural systems, agricultural producers, and market processes will react.

Still, the science is clear: climate change is occurring. No Montana producer is guaranteed the status quo—change is happening, even if we cannot yet unravel all its components. Precise projections need not be a prerequisite for mitigation and adaptation. Instead, maintaining or increasing resilience in Montana's agriculture system is paramount.

That resilience will most likely come from increased diversity in our agricultural products and practices. Montana agriculture already includes a spectrum of strategies, for example, global and local marketing; cropping and livestock; feed yard and grass finishing; and pulse groups and crop/fallow small grain crops. Under climate change, new strategies—for example, breeding forages that are tolerant to high temperature or crops and livestock that are resistant to pathogens—may be necessary. Likewise, the prominence of each strategy may well change, and with it the relative economic importance to our state.

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South of Glasgow, northeast Montana.
Photograph courtesy of Rick and Susie Graetz, University of Montana.

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CLOSING REMARKS

06. KEY KNOWLEDGE GAPS ADDRESSING CLIMATE CHANGE IN MONTANA

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Montanans need to fill many gaps in our knowledge if we are to better understand and thrive under a changing climate. Below, we list research that is needed to achieve better understanding of direct effects, indirect effects, and general effects of climate change in Montana. These suggestions are included in each sector chapter of this assessment, and are compiled here for easy reference.

CLIMATE

- Additional climate variables.—Our analysis provides a critical local look at changes for two important climate variables, precipitation and temperature. However, Montana's climate and its impacts go beyond these. A more in depth downscaling effort that involves physics based models will be required to evaluate two additional important variables, evapotranspiration and drought.
- Land use and land cover change.—Most climate analyses do not account for changes in land cover with climatic trends. However, interactions between climate, vegetation cover, and land use quality are tightly coupled. For example, with changes in temperature and precipitation, ecosystems within Montana may shift to drier conditions resulting in changes to vegetation types. This would contribute to a difference in evapotranspiration rates and aridity.
- Precipitation timing and form.—We took a first look at changes in Montana's precipitation. However, it is well known that the timing (winter versus spring and summer) and form (rain versus snow) of Montana's precipitation is critical for areas such as water, forests, and agriculture resources. More work that incorporates physically based, distributed hydrological models is required to understand how our precipitation distribution will change in both space (low elevations to mountaintops) and time.

WATER

- Water demand and management in the context of a changing climate.— Although the direct influences of climate change on water supply have received substantial attention (as evidenced by this assessment), much less is known about the intersection between changes in climate and water demand and/or water management. New solutions are needed that balance the multiple, and sometimes competing, demands for water in the context of changing or shifting water supplies. Communication and collaboration among multiple stakeholders, including universities, agencies, non-governmental organizations, and citizen groups will be paramount. The regional basin water plans in Montana represent a bold and critical first step, but there is much work to be done.
- Improving the accuracy of models in Montana.—Many of the downscaled climate-hydrology projections are not yet calibrated for specific basins across Montana. Thus, when the models agree, we have relatively high confidence in the direction of projected changes, but much less confidence in the magnitude of future changes for specific river basins. The collaboration between MT DNRC and the Bureau of Reclamation and other ongoing efforts associated with the Northwest Climate Science Center are helping to close this gap, but additional modeling and local hydrologic expertise will be needed.

In addition, we know that groundwater-surface water interactions are central for projecting climate change impacts on water resources, particularly in snowmelt-dominated watersheds. These interactions are not typically integrated in hydrologic models, but such efforts will be necessary for improving our projections about climate change and water supply.

- Maintain and expand our water monitoring network.—Our knowledge about current and future water supplies depends critically on our ability to monitor the water cycle across Montana and beyond. Our current network of weather stations, streamflow gages, groundwater wells, and snowpack monitoring sites must be maintained and expanded to better represent ongoing changes in the state. Current collaborations between USGS, Montana Bureau of Mines and Geology, and the Montana DNRC are helping to support this monitoring network, but additional investment in this area will serve as insurance for managing a sustainable water future.

FORESTS

- Better understanding of direct climate change effects.—a) Improved understanding of adaptive genetic and phenotypic forest characteristics that would provide better guidance for breeding programs and management actions to maximize resilience to both direct and indirect climate impacts to forests; b) Long-term studies to better understand effects of CO_2 fertilization in Montana's forests; c) Improved models of climate and vegetative effects on evapotranspiration and water balances throughout forested systems.

- Better understanding of indirect climate change effects.—a) Improved fire models and projections directly related to Montana's forests; b) Long-term monitoring of forest insect and pathogen response to recent climate changes and improved projections of future likely impacts; c) Better understanding of disturbance effects on microclimates and refugia and implications for forest productivity, mortality, and adaptation.

- General effects and adaptation options.—a) Forest models that account for changes in both climate and resulting vegetation distribution and patterns; b) Models that account for interactions and feedbacks in climate-related impacts to forests (e.g., changes in mortality from both direct increases in warming and increased fire risk as a result of warming); c) Systems thinking and modeling regarding climate effects on understory vegetation and interactions with forest trees; d) Discussion of climate effects on urban forests and impacts to cityscapes and livability; e) Monitoring and time-series data to inform adaptive management efforts (i.e., to determine outcome of a management action and, based on that outcome, chart future course of action); f) Detailed decision support systems to provide guidance for managing for adaptation.

AGRICULTURE

- Precipitation.—With the high certainty of warming and the low certainty of trends in precipitation, how do we develop resilient agricultural practices that prepare for divergent futures?
- Crop and livestock models.—a) How can crop and forage production models linked with climate models provide useful projections to inform agricultural decisions? b) Which models best inform management of livestock under predicted new climates? c) What mechanisms for data acquisition and accessibility allow appropriate climate and production model parameterization?
- Water.—a) When and where will irrigation be most disrupted as temperatures rise and water storage declines? b) How can we modify our methods for water retention, allocation, and efficiency to increase crop and livestock resilience to climate variability?
- Soil carbon.—a) In which systems and regions can improving soil organic matter help build resilience under volatile climate conditions, including severe drought? b) How can grassland protection and restoration help increase resilience to climate changes, as well as be integrated into food production? c) Which agricultural practices will build soil carbon reserves and serve as viable greenhouse gas mitigation strategies?
- Input practices.—a) Can inputs continue to be used as insurance to protect against variation? b) Does dependence on inputs contribute to creating less resilient agricultural systems? c) Can some inputs increase resilience?
- Commodity markets.—a) How can increased value-added production practices reduce dependence on volatile commodity pricing and thereby build resilience? b) When and where do traditional methods for farmer and consumer protection (e.g., crop insurance, government reserves) need revision to more effectively respond to climate-change uncertainty? c) How can revision of commodity market practices and expectations help develop resilience in anticipation of climate-change induced volatility? d) What improvements in enterprise-level financial and risk management strategies are needed to better manage market and production risks?
- Crop and livestock diversity.—a) How can introduction of diversity to cropping and livestock selections and systems help build resilience to climate change? b) In which current homogeneous production systems can diversity be reintroduced without economic loss? c) How may increased agricultural diversity impact quantity and quality of goods produced in agriculture?

- Policy—a) Which state and national policies influence producer's ability to adopt more resilient practices to climate change? b) What role can Montana seed providers, food processors and distributors play to increase agricultural resilience in the face of the uncertainty presented by climate change?

- Rural Sustainability—a) How will agricultural communities be maintained and need to change in response to climate change? b) How will decisions at all spatial and temporal scales need to change to increase resilience to climate change?

New research into these areas will improve our understanding and knowledge of how climate change will impact Montana in the future. Along with scientific investigations, Montanans need to work together to effectively:

- consider multiple sources of information, including indigenous knowledge and historical observations, which can complement and enrich empirically-based studies and modeling approaches;

- build a community of scientists and practitioners that can better create a research agenda on the highest priority topics and needs of decision makers; this collaboration will produce actionable science and tangible outcomes; and

- improve education and communication activities related to climate science across the state so that adaptation plans reach the most relevant and most impacted sectors of our communities.

Beartooth Mountains.
Photograph courtesy of Scott Bischke.

GLOSSARY

adaptation Actions taken to help communities and ecosystems better cope with potential negative effects of climate change or take advantage of potential opportunities.

adaptive capacity The inherent ability of a system (e.g., ecosystem or social system) to adapt to a changing environment; for example, a plant species that can survive a broader range of temperatures may have greater adaptive capacity compared to a plant that can only tolerate a narrow range of temperatures.

agribusiness An industry engaged in the production operations of a farm, the manufacture and distribution of farm equipment and supplies, and the processing, storage, and distribution of farm commodities.

agronomy The science of crop production and soil management.

annual streamflow The cumulative quantity of water for a period of record, in this case a calendar year.

anthropogenic Originating in human activity.

aquifer A body of permeable rock that can contain or transmit groundwater.

atmospheric carbon dioxide (CO_2) The amount of CO_2 in Earth's atmosphere. Although the proportion of Earth's atmosphere made up by CO_2 is small, CO_2 is a potent greenhouse gases and directly related to the burning of fossil fuels. Atmospheric carbon dioxide levels in Earth's atmosphere are at the highest levels in an estimated 3 million years and these levels are projected to increase global average temperatures through the greenhouse effect.

attribution Identifies a source or cause of something.

basis The difference between the futures market price and the local price for an agricultural commodity, measured in dollars per bushel.

base flow The portion of streamflow that is not runoff and results from seepage of water from the ground into a channel slowly over time. The primary source of running water in a stream during dry weather.

basin A drainage basin or catchment basin is an extent or an area of land where all surface water from rain, melting snow, or ice converges to a single point at a lower elevation, usually the exit of the basin, where the waters join another body of water, such as a river, lake, reservoir, estuary, wetland, sea, or ocean.

biocontrol Short for biological control; the reduction in numbers or elimination of pest organisms by interference with their ecology (as by the introduction of parasites or disease).

biodiversity The variety of all native living organisms and their various forms and interrelationships.

biomass The total amount of organic matter present in an organism, population, ecosystem, or given area.

bushel A unit for measuring an amount of fruit and grain that is equal to about 35.2 liters in the US.

C3 and C4 plants Plants use different photosynthetic pathways (termed C3 photosynthesis or C4 photosynthesis). C4 plants evolved as an adaptation to high-temperature, high-light conditions. C4 plant growth rates increase more under hot, high-CO_2 conditions than that of C3 plants and exhibit less water loss.

climate versus weather The difference between weather and climate is a measure of time. Weather is what conditions of the atmosphere are over a short period of time, and climate is how the atmosphere behaves over relatively long periods of time (i.e., multiple decades).

climate change Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system.

climate oscillation See teleconnections.

commercial crops Agricultural crops that are grown for sale to return a profit, purchased by parties separate from a farm (note: not all commercial crops are commodity crops).

commodity crops Crops that are traded, and typically include crops that are non-perishable, easily storable, and undifferentiated.

commodity futures Buying or selling of a set amount of a commodity at a predetermined price and date.

confined aquifer A confined aquifer is an aquifer below the land surface that is saturated with water. Layers of impermeable material are both above and below the aquifer, causing it to be under pressure so that when the aquifer is penetrated by a well, the water will rise above the top of the aquifer.

cow-calf operations Livestock operations in which a base breeding herd of mother cows and bulls are maintained. Each year's calves are sold between the ages of 6 and 12 months, along with culled cows and bulls, except for some breeding herd replacements.

crop rotation System of cultivation where different crops are planted in consecutive growing seasons to maintain soil fertility.

cultivar A contraction of cultivated variety. It refers to a plant type within a particular cultivated species that is distinguished by one or more characteristics.

direct effect A primary impact to a system from shifts in climate conditions (e.g., temperature and precipitation), such as direct mortality to species from increased heat extremes.

direct runoff The runoff entering stream channels promptly after rainfall, exclusive of base flow. Direct runoff equals the volume of rainfall excess (e.g., total precipitation minus losses).

disturbance regime The frequency, severity, and pattern of events that disrupt an ecosystem or community; for example, a forest's fire disturbance regime may be the historical pattern of frequent, low-intensity fires versus infrequent, high-severity fires.

drought For this report, drought is categorized in four ways: 1) meteorological drought, defined as a deficit in precipitation; 2) hydrological drought, characterized by reduced water levels in streams, lakes, and aquifers; 3) ecological drought, defined as a prolonged period over which an ecosystem's demand for water exceeds the supply; and 4) agricultural drought, commonly understood as a deficit in soil moisture.

dryland farming A system of producing crops in semiarid regions (usually with less than 20 inches [0.5 m] of annual rainfall) without the use of irrigation.

El Niño-Southern Oscillation (ENSO) A periodic variation in wind and sea-surface temperature patterns that affects global weather; El Niño (warming phase where sea-surface temperatures in the eastern Pacific Ocean warm) generally means warmer (and sometimes slightly drier) winter conditions in Montana. In contrast, La Niña (cooling phase) generally means cooler (and sometimes wetter) winters for Montanans.The two phases each last approximately 6-18 months, and oscillate between the two phases approximately every 3-4 yr.

ensemble of general circulation models (GCMs) Succinctly: When many different forecast models are used to generate a projection, and outputs are synthesized into a single score or average. This type of forecast significantly reduces errors in model output and enables a level of certainty to be placed on the projections. More broadly: Rather than relying on the outcome of a single climate model, scientists run ensembles of many models. Each model in the ensemble plausibly represents the real world, but as the models differ somewhat they produce different outcomes. Scientists analyze the outputs (e.g., projected average daily temperature at mid century) over the entire ensemble. Those analyses provide both the projection of the future resulting from the ensemble of models, and define the level of certainty that should be placed on that projection.

ephemeral stream A stream that flows only briefly during and following a period of rainfall in the immediate locality.

evaporation The change of a liquid into a vapor at a temperature below the boiling point. Evaporation takes place at the surface of a liquid, where molecules with the highest kinetic energy are able to escape. When this happens, the average kinetic energy of the liquid is lowered and its temperature decreases.

evapotranspiration The combined effect of evaporation and transpiration (by plants) of water, which is one of the most important processes driving the hydrologic cycle. Evapotranspiration is often analyzed in two ways, as potential evapotranspiration, which is a measure of demand for water from the atmosphere regardless of how much water is available, and actual evapotranspiration, which is how much water is actually used by plants and evaporated from water surfaces. Generally, actual evapotranspiration is driven by water availability, solar radiation, and plant type, but also affected by wind and vapor pressure. Transpiration is affected by vegetation-related factors such as leaf area and stomatal conductance, the exchange of CO_2 and water vapor between leaves and the air.

fallow Cultivated land that is allowed to lie idle during the growing season; or to plow, harrow, and break up (land) without seeding to destroy weeds and conserve soil moisture.

feeder cattle Growing beef cattle between the calf stage and sale to finishing operations.

fire behavior The manner in which wildfire ignites and spreads, and characterizing the burning conditions within a single fire.

fire regime The frequency, severity, and pattern of wildfire.

fire risk The likelihood of a fire ignition.

fire severity The magnitude of effects from a fire, usually measured by the level of vegetation or biomass mortality or the area burned.

flood An overflowing of a large amount of water beyond its normal confines, especially over what is normally dry land.

flood plain An area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.

frost days The annual count of days where daily minimum temperature drops below 32°F (0°C).

futures trading An agreement between two people, one who sells and agrees to deliver and one who buys and agrees to a certain kind, quality, and quantity of product to be delivered during a specified delivery month at a specified price. More simply, a contract to buy specific quantities of a commodity at a specified price with delivery set at a specified time in the future.

general circulation models (GCMs) Numerical models representing physical processes in the atmosphere, ocean, cryosphere, and land surface. They are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations.

grain filling The period of wheat development from pollination to seed production.

greenhouse gas A gas in Earth's atmosphere that absorbs and then re-radiates heat from the Earth and thereby raises global average temperatures. The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Earth relies on the warming effect of greenhouse gases to sustain life, but increases in greenhouse gases, particularly carbon dioxide from the burning of fossil fuels, can increase average global temperatures over historical norms.

greenhouse gas emissions The discharge of greenhouse gases, such as carbon dioxide, methane, nitrous oxide and various halogenated hydrocarbons, into the atmosphere. Combustion of fossil fuels, agricultural activities, and industrial practices contribute to the emissions of greenhouse gases.

green manure Crops grown to be incorporated into the soil to increase soil quality, fertility and structure.

global warming The increase in Earth's surface air temperatures, on average, across the globe and over decades. Because climate systems are complex, increases in global average temperatures do not mean increased temperatures everywhere on Earth, nor that temperatures in a given year will be warmer than the year before (which represents weather, not climate). More simply: Gobal warming is used to describe a gradual increase in the average temperature of the Earth's atmosphere and its oceans, a change that is believed to be permanently changing the Earth's climate.

groundwater Water held underground in the soil or in pores and crevices in rock.

growing degree-days A weather-based indicator for assessing crop development. It is a calculation used by crop producers that is a measure of heat accumulation used to predict plant and pest development rates such as the date that a crop reaches maturity.

hardiness zone A geographically-defined zone in which a specific category of plant life is capable of growing, as defined by temperature hardiness, or ability to withstand the minimum temperatures of the zone. The zones are based on the average annual extreme minimum temperature during a 30-yr period in the past, not the lowest temperature that has ever occurred in the past or might occur in the future.

human agency The capacity possessed by people to act of their own volition.

hydrograph A hydrograph is a graph showing the rate of flow (discharge) versus time past a specific point in a river, or other channel or conduit carrying flow. The rate of flow is typically expressed as cubic feet per second, CFS, or ft^3/s (the metric unit is m^3/s).

hydrologic cycle The sequence of conditions through which water passes from vapor in the atmosphere through precipitation upon land or water surfaces and ultimately back into the atmosphere as a result of evaporation and transpiration.

hydrology The study of water. Hydrology generally focuses on the distribution of water and interaction with the land surface and underlying soils and rocks.

indirect effect A secondary impact to a system from a change that was caused by shifting climate conditions, such as increased fire frequency, which is a result of drier conditions caused by an increase in temperature.

infiltration The movement of water from the land surface into the soil.

interception The capture of precipitation above the ground surface, for example, by vegetation or buildings.

IPCC SRES Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios.

irrigation Application of water to soil for the purpose of plant production.

legume Any of a large family (Leguminsoae syn. Fabaceae, the legume family) of dicotyledonous herbs, shrubs, and trees having fruits that are legumes or loments, bearing nodules on the roots that contain nitrogen-fixing bacteria, and including important food and forage plants (as peas, beans, or clovers).

metrics Quantifiable measures of observed or projected climate conditions, including both primary metrics (for example, temperature and precipitation) and derived metrics (e.g., projected days over 90°F [32°C] or number of consecutive dry days).

microclimate The local climate of a given site or habitat varying in size from a tiny crevice to a large land area. Microclimate is usually, however, characterized by considerable uniformity of climate over the site involved and relatively local when compared to its enveloping macroclimate. The differences generally stem from local climate factors such as elevation and exposure.

mitigation Efforts to reduce greenhouse gas emissions to, or increase carbon storage from, the atmosphere as a means to reduce the magnitude and speed of onset of climate change

model A physical or mathematical representation of a process that can be used to predict some aspect of the process.

organic A crop that is produced without: antibiotics; growth hormones, most conventional pesticides, petroleum-based fertilizers or sewage sludge-based fertilizers, bioengineering, or ionizing radiation. USDA certification is required before a product can be labeled organic.

oscillation A recurring cyclical pattern in global or regional climate that often occurs on decadal to sub-decadal timescales. Climate oscillations that have a particularly strong influence on Montana's climate are the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

Pacific Decadal Oscillation (PDO) A periodic variation in sea-surface temperatures that is similar to El Niño-Southern Oscillation, but has a much longer duration (approximately 20-30 yr). When the PDO is in the same phase as El Niño-Southern Oscillation, weather effects are more pronounced. For example, when both are in the warming phase, Montanans may experience an extremely warm winter, whereas if PDO is in a cooling phase, a warm phase El Niño-Southern Oscillation may have a reduced impact.

Palmer Drought Severity Index (PDSI) A measurement of dryness based on recent precipitation and temperature. The Palmer Drought Severity Index is based on a supply-and-demand model of soil moisture.

Palmer Z Drought Index One of the Palmer Drought Indices; it measures short-term drought on a monthly scale. The Z-value is also referenced to the specific location, climate, and time of year.

parameter A variable, in a general model, whose value is adjusted to make the model specific to a given situation.

pathogen Microorganisms, viruses, and parasites that can cause disease.

peak flow The point of the hydrograph that has the highest flow.

permeability A measure of the ability of a porous material (often, a rock or an unconsolidated material) to allow fluids to pass through it.

phenology The study of periodic biological phenomena with relation to climate (particularly seasonal changes). These phenomena can be used to interpret local seasons and the climate zones.

physiography The subfield of geography that studies physical patterns and processes of the Earth. It aims to understand the forces that produce and change rocks, oceans, weather, and global flora and fauna patterns.

primary productivity The total quantity of fixed carbon (organic matter) per unit area over time produced by photosynthesis in an ecosystem.

pulse crop Annual leguminous crops yielding from 1-12 grains or seeds of variable size, shape, and color within a pod. Limited to crops harvested solely for dry grain, thereby excluding crops harvested green for food, oil extraction, and those that are used exclusively for sowing purposes.

radiative forcing The difference between the amount of sunlight absorbed by the Earth versus the energy radiated back to space. Greenhouse gases in the atmosphere, particularly carbon dioxide, increase the amount of radiative forcing, which is measured in units of watts/m^2. The laws of physics require that average global temperatures increase with increased radiative forcing.

rangeland Land on which the historical climax plant community is predominantly grasses, grasslike plants, forbs, or shrubs. This includes lands re-vegetated naturally or artificially when routine management of the vegetation is accomplished through manipulation of grazing. Rangelands include natural grasslands, savannas, shrublands, most deserts, tundra, alpine communities, coastal marshes, and wet meadows

RCP (representative concentration pathways) Imagined plausible trends in greenhouse gas emissions and resulting concentrations in the atmosphere used in climate projection models. This analysis uses the relatively moderate and more severe scenarios of RCP4.5 and 8.5. These scenarios represent a future with an increase in radiative forcing of 4.5 or 8.5 watts/m^2, respectively. The RCP4.5 scenario assumes greenhouse gas emissions peak mid century, and then decline, while the RCP8.5 scenario assumes continued high greenhouse gas emissions through the end of the century.

resilience In ecology, the capacity of an ecosystem to respond to a disturbance or perturbation by resisting damage and recovering quickly.

resistance In ecology, the property of populations or communities to remain essentially unchanged when subject to disturbance. Sensitivity is the inverse of resistance.

resistance gene A gene involved in the process of resistance to a disease or pathogen; especially a gene involved in the process of antibiotic resistance in a bacterium or other pathogenic microorganism.

ruminants Mammals that have four stomachs and even-toed hooves.

runoff Surface runoff (also known as overland flow) is the flow of water that occurs when excess stormwater, meltwater, or other sources flows over the Earth's surface.

scenario Climate change scenarios are based on projections of future greenhouse gas (particularly carbon dioxide) emissions and resulting atmospheric concentrations given various plausible but imagined combinations of how governments, societies, economies, and technologies will change in the future. This analysis considers two plausible greenhouse gas concentration scenarios: a moderate (stabilized) and more severe (business-as-usual) scenario, referred to as RCP4.5 and RCP8.5, respectively

shallow aquifer Typically (but not always) the shallowest aquifer at a given location is unconfined, meaning it does not have a confining layer (an aquitard or aquiclude) between it and the surface. The term perched refers to ground water accumulating above a low-permeability unit or strata, such as a clay layer.

silage Any crop that is harvested green and preserved in a succulent condition by partial fermentation in a nearly airtight container such as a silo.

specialty crop Fruits and vegetables, tree nuts, dried fruits and horticulture and nursery crops, including floriculture.

spring wheat A general term for wheat sown in the early spring and harvested in the late summer or early autumn of the same year.

Snow Water Equivalent (SWE) A common snowpack measurement that is the amount of water contained within the snowpack. It can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instantaneously.

soil moisture A measure of the quantity of water contained in soil. Soil moisture is a key variable in controlling the exchange of water and energy between the land surface and the atmosphere through evaporation and plant transpiration.

storage The volume of water contained in natural depressions in the land surface, such as a snowpack, glaciers, drainage basins, aquifers, soil zones, lakes, reservoirs, or irrigation projects.

streamflow (also known as channel runoff) The flow of water in streams, rivers, and other channels. It is a major element of the water cycle.

teleconnection A connection between meteorological events that occur a long distance apart, such as sea-surface temperatures in the Pacific Ocean affecting winter temperatures in Montana. Also referred to as climate oscillations or patterns of climate variability.

test weight A measure of grain bulk density, often used as a general indicator of overall quality and as a gage of endosperm hardness to alkaline cookers and dry millers.

tillage The traditional method of farming in which soil is prepared for planting by completely inverting it with a plow. Subsequent working of the soil with other implements is usually performed to smooth the soil surface. Bare soil is exposed to the weather for some varying length of time depending on soil and climate conditions.

transpiration The passage of water through a plant from the roots through the vascular system to the atmosphere.

unconfined aquifer A groundwater aquifer is said to be unconfined when its upper surface (water table) is open to the atmosphere through permeable material.

velocity The rate of climate changes occurring across space and time.

warm days Percentage of time when daily maximum temperature >90th percentile.

warm nights Percentage of time when daily minimum temperature >90th percentile.

water quality The chemical, physical, biological, and radiological characteristics of water. It is a measure of the condition of water relative to the requirements of one or more biotic species and/or to any human need or purpose.

watershed An area characterized by all direct runoff being conveyed to the same outlet. Similar terms include basin, subwatershed, drainage basin, catchment, and catch basin.

water year A time period of 12 months (generally October 1 of a given year through September 30 of the following year) for which precipitation totals are measured.

weather versus climate See climate versus weather.

winter wheat A general term for wheat sown in the fall, persisting through the winter winter as seedlings, and harvested the following spring or summer after it reaches full maturity.


Snow geese on Freeze Out Lake.
Photograph courtesy of Scott Bischke.

LIST OF CONTRIBUTORS

Thomas R. Armstrong is President of the Madison River Group (MRG) and served as a senior advisor for the Montana Climate Assessment. He also serves as an Affiliate Faculty Member at Montana State University. Prior to MRG, Dr. Armstrong served within the White House Office of Science and Technology Policy as the Executive Director of the United States Global Change Research Program. He was the lead in the development of the USGCRP's new Ten Year Strategic Plan and a key player in the Third National Climate Assessment, the President's Climate Action Plan, and other activities related to the federal climate change enterprise. He also served as the US Head of Delegation to the Intergovernmental Panel on Climate Change Fifth Assessment Report. Before Joining the White House, Tom served as the Department of the Interior's Senior Advisor for Climate Change.

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Anton Bekkerman is an Associate Professor in the Department of Agricultural Economics and Economics at Montana State University. His research interests include price analysis in grain markets, agricultural marketing, and the economics of production and management in the agricultural industry. Anton's recent research focus has been on improving wheat price predictions for the northern United States, identifying the economic impacts of changes in the grain handling industry, and understanding the market-level impacts of increased pulse production in Montana. On campus, Anton teaches the Economics of Agricultural Marketing and Managerial Economics courses and is a faculty advisor to a collegiate student club.

Scott Bischke of MountainWorks Inc. served the Montana Climate Assessment as Science Writer. Scott is a BS (Montana State University), MS (University of Colorado) chemical engineer who has worked as an engineering researcher at three national laboratories: the National Bureau of Standards (now National Institute of Science and Technology), Sandia, and Los Alamos. He worked for roughly 11 yr as lead environmental engineer for a Hewlett-Packard business unit. Scott has authored, co-authored, or edited two environmental impact statements, book chapters, technical papers, four popular press books, and successful proposals totaling multiple-millions of dollars.

Madison Boone graduated from Hendrix College with degrees in Biology and Environmental Studies. She has worked for Heifer International's Heifer Farm in Rutland, MA where she was a livestock steward and led educational programs. Madison moved to Bozeman, MT in January 2016 to serve with the Big Sky Watershed Corps, through which she worked for the non-profit One Montana on their Resilient Montana program. She is now serving a second term of the Big Sky Watershed Corps program in 2017, during which she will continue to work with One Montana as well as MSU-Extension on their Climate Science Team.

Samantha Brooks is the Lead Director for Science, Policy and Programs at Madison River Group (MRG) and an advisor to the Montana Climate Assessment. Prior to MRG, Ms. Brooks served for 3 yr with the US Global Change Research Program (USGCRP) as Executive Secretary, and a member of the USGCRP Leadership Team, providing strategic advice and direction to the White House Subcommittee on Global Change Research (SGCR). Her academic background is in international environmental policy with a particular focus on climate change. She holds a BA in International Relations from James Madison University and MA in Global Environmental Policy from American University. She holds the title of Affiliate Professor in Political Science at Montana State University.

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Mary Burrows obtained her PhD in Plant Pathology from the University of Wisconsin-Madison. She started her position as the Extension Plant Pathology Specialist at Montana State University in August of 2006. Her extension and research activities focus on diseases of field crops. She directs the Schutter Plant Diagnostic Laboratory, the Regional Pulse Crop Diagnostic Laboratory, serves as the Integrated Pest Management coordinator for Montana, the IR-4 Project State Liaison Representative, and has an active applied research program.

Wyatt F. Cross is Director of the Montana University System Water Center, and an Associate Professor of Ecology at Montana State University. His current research focuses on ecological responses of streams and rivers to human activities, including climate warming, river regulation, and nutrient enrichment. Wyatt is also working to strengthen connections between the Montana university system and state agencies and non-governmental organizations in the context of water resource science and management.

Edward Dunlea is the Chief Scientist for Madison River Group. Prior to MRG, he was a Senior Program Officer at the National Academies of Sciences, Engineering, and Medicine with the Board on Atmospheric Sciences and Climate; he led studies on high profile topics in climate and atmospheric sciences, including climate intervention (geoengineering), seasonal forecasting, abrupt climate changes, and climate modeling. Previously, Edward was a Program Manager for the National Oceanic and Atmospheric Administration in the Climate Program Office, and a post-doctoral researcher in atmospheric chemistry at the University of Colorado and the Massachusetts Institute of Technology. Edward holds a doctorate in atmospheric physical chemistry from the University of Colorado and an AB in chemistry from Harvard University.

Paul Herendeen is an environmental scientist and engineer, working to provide practical solutions to environmental problems. Initially trained in research, he worked in silviculture, hydrology, and biogeochemistry for the US Geological Survey and Forest Service. After earning a graduate degree, he has shifted his focus to the built environment, with the goal of integrating human activity into the natural world. He holds a BA in Biology from the University of Virginia and a MS in Biological & Environmental Engineering from Cornell University.

Laura Ippolito is an honors student and sophomore at MSU dual majoring in Economics and Sustainable Foods and Bioenergy Systems with a concentration in Agroecology. She graduated from Phillips Academy Andover in May of 2014, and took a gap year before attending MSU in the fall of 2015. During her gap year, Laura got her certified Wilderness EMT license from NOLS, worked on a permaculture farm in Ecuador, and volunteered in Nepal and Thailand. At school, Laura is still working on agricultural research under the guidance of Bruce Maxwell.

Kelsey Jencso is an Associate Professor of Watershed Hydrology at the University of Montana and the Director of the Montana Climate Office. His research focuses on forested mountain watersheds and the mechanisms that influence forest growth and the movement of water, nutrients, and sediment in upland and aquatic environments. In his capacity as the Montana State Climatologist, Kelsey is leading efforts to provide climate and meteorological information to the public in a user specific context, the development of a statewide soil moisture and weather measurement network, and a collaborative effort to develop satellite based evapotranspiration and water deficit tools in agriculture and rangeland settings.

W. Matt Jolly is a Research Ecologist in the Fire, Fuel and Smoke Science Program at the US Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory. His research explores the influence of live fuels on wildland fire behavior and it also explores ways to use this improved understanding to develop predictive tools that can help support strategic and tactical wildland fire management decisions.

John LaFave is a senior research hydrogeologist and manages the Montana Ground Water Assessment Program at the Montana Bureau of Mines and Geology. His research interests include characterizing large groundwater flow systems and identifying areas of anthropogenic recharge in western Montana using environmental tracers, long-term water level measurements and water chemistry data. John has Bachelor's degree in Geology from the University of Wisconsin and a Master's degree in Geology from the University of Texas.

Andrew J. Larson is Associate Professor of Forest Ecology at the University of Montana. His research examines disturbances and dynamics of forest ecosystems, including forest management strategies for forest restoration and climate change adaptation and mitigation. Themes in his research program include forest productivity and carbon storage; rates, causes, and consequences of tree mortality; development and functional consequences of spatial heterogeneity in forest ecosystems; and fire-effects and succession in mixed-conifer forests. Dr. Larson instructs at UM and serves as Associate Editor for the journal Fire Ecology. His fire ecology research in the Bob Marshall Wilderness was recognized with the USDA Forest Service National Award for Wilderness Stewardship Research.

Alex Leone works for the Clark Fork Coalition on stream restoration in the Upper Clark Fork focusing on water planning efforts and conservation projects aimed at enhancing flows and restoring aquatic habitat. Alex has spent most of his life in Montana and attended both the University of Montana (BS in Forest Management) and Montana State University (MS in Earth Sciences). Alex spends the majority of his free time chasing trout on Montana's seemingly endless supply of streams and exploring wilderness areas in the Northern Rockies.

Whitney Lonsdale has a strong interest in climate change and water resources in Montana and the West, particularly water scarcity and its implications for human and ecological systems. With a background in education and a graduate degree in Natural Resources from Cornell University, Whitney is dedicated to informing strategies that build resilience in Montana and bringing science to the public in ways that are relevant and accessible. Whitney joined the Montana University System Water Center as Assistant Director in early 2017.

Bruce Maxwell is Professor of Agroecology and Applied Plant Ecology in the Department of Land Resources and Environmental Science (LRES) and co-Director of the Montana Institute on Ecosystems at Montana State University. Maxwell was instrumental in the formation of the Department of LRES and has received national awards for outstanding teaching, best peer reviewed papers and outstanding graduate student from the Weed Science Society of America. He has published over 100 scientific journal articles and book chapters, chaired and been a member of numerous agricultural and ecological research grant review panels and been a member of two National Academy of Science National Research Council Committees on Agriculture. He was a Fulbright Fellow in Argentina in 2007. His research has historically straddled the disciplines of invasion biology and agroecology.

Stephanie McGinnis is the outgoing Assistant Director of the Montana Water Center and the Coordinator of Education and Outreach at Montana Watercourse. Throughout her career, Stephanie has been heavily involved in environmental education and outreach, working for public schools, state and federal agencies, and currently as an adjunct faculty member at MSU. She has also conducted research in Montana and Wyoming focused on the conservation and restoration of freshwater ecosystems.

Megan Mills-Novoa is a PhD student in the School of Geography and Development at the University of Arizona. A native Minnesotan, Megan graduated with a BA in environmental studies and biology from Lewis & Clark College in 2009. Following graduation, Megan worked as a Fulbright Scholar with the Global Change Center in Santiago, Chile and as a Luce Scholar with the Centre for Sustainable Development in Hanoi, Vietnam. In the summer of 2016, Megan worked as a Sustainability Fellow with One Montana where she worked with the Montana Climate Assessment team.

Thomas Patton holds a MS in Geology from Montana Tech and is the Research Division Chief at the Montana Bureau of Mines and Geology. Tom was instrumental in early development of Montana's Ground Water Information Center and Montana's first statewide long-term groundwater monitoring network. His research interests include relationships between groundwater-level changes in wells and departures from average precipitation at various accumulation periods.

Alisa Royem grew up in the West and is deeply concerned with water resources, water rights, and climate change. She has a BS in Environmental Biology from Fort Lewis College and an MS in Hydrology and Natural Resources from Cornell University. Today she lives in Montana where she works with emerging water issues, climate change, mitigation, and resilience.

Nick Silverman is a Research Scientist at the University of Montana. His academic interests include mountain landscape hydroclimatology, remote sensing, land surface modeling, and hydroeconomics. Nick has received an MS from the University of Washington and a PhD from the University of Montana in Regional Hydroclimatology. Nick is passionate about making connections between science, people and policy. He spends his free time speaking to farmers, ranchers, government agencies, and water resource professionals throughout Montana about impacts and adaptations related to climate and water interactions.

Kristina Sussman has over 11 yr experience in brand and marketing communication strategy, graphic and web design. She has her Bachelors in Graphic Design and is the UX/UI Designer and Marketing Strategist with the Madison River Group (MRG) team. She was the Lead Web Designer for 5 yr at the USGS and recently launched their new Drupal website in April 2016. Kristina has designed a variety of marketing and branding materials to include brand strategies, style guides, logos, identity packaging, direct and email marketing, animations/video, website design, exhibits, infographics, advertising, and more.

Michael Sweet is a data manager and analyst with the Montana Climate Office at the University of Montana. After a 27-yr stint in applied forest management research, in 2010 Mike was presented with the opportunity to revive the dormant Montana Climate Office. He enjoys problem solving and the challenge of packaging information into a tasty morsel. When he's not attached to a keyboard you will find him on the water, in the mountains, on the dance floor, working in the garden, or playing music.

Anna Tuttle is the Program and Communications Manager for the Institute on Ecosystems (IoE) at Montana State University (MSU), and is also a non-tenure track faculty member at MSU. After receiving her MS in Environmental Studies from the University of Montana, Anna spent 10 yr teaching leadership, communication, safe backcountry travel, and college-level academics for several field-based schools and university programs. This work involved researchers, ecologists, ranchers, farmers, tribal members, educators, and guides from across the country.

Alisa A. Wade is an Affiliate Faculty member at the University of Montana. She is a conservation scientist with a particular interest in bridging the gap between science and management by creating analytical and decision-making tools for conservation planning. Dr. Wade's research has focused on assessing climate change vulnerability across broad spatial scales, with a particular emphasis on freshwater ecosystems. She earned degrees in political science (BA, UC Santa Barbara), public administration and environmental policy (MPA, San Jose State University), environmental planning (MCP, UC Berkeley) and Earth science (PhD, Colorado State University), and she completed her post-doctorate position at the National Center for Ecological Analysis and Synthesis.

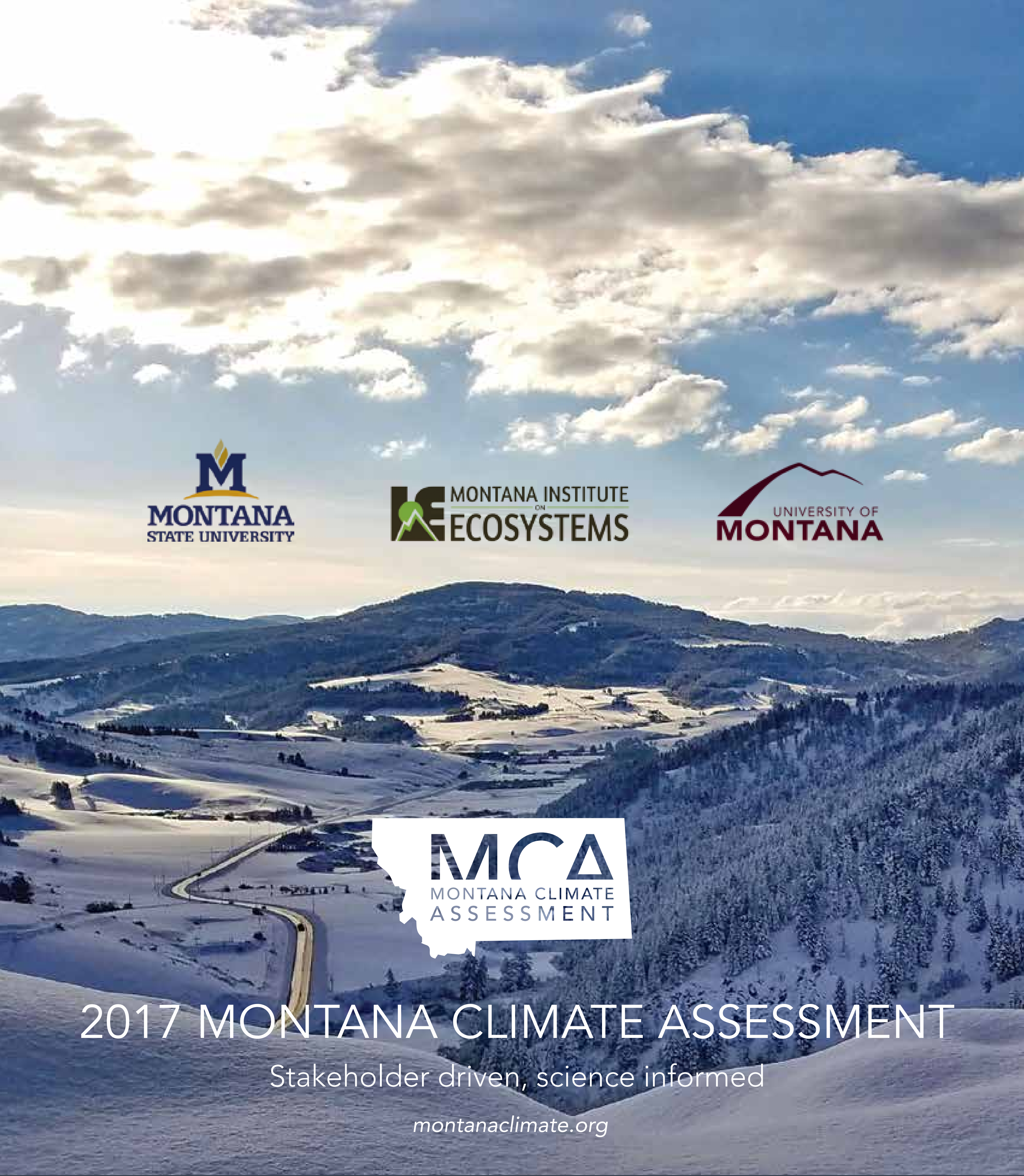
David Weaver is Professor of Entomology in the Department of Land Resources and Environmental Science at Montana State University. Prior to MSU, he worked for USDA-ARS for several years on automated detection of insects in stored grain, insect biological control and insect ecology. He is former editor-in-chief for the *Journal of Agricultural and Urban Entomology* and has published over 100 scientific journal articles, in addition to book chapters and outreach materials. Since 1997, he has worked primarily on the chemical ecology, biological control, and biorational management of agricultural pests. A particular focus is the wheat stem sawfly, a native pest that has damaging populations that are currently expanding southward.

Becky Weed is currently a research associate at Montana State University, combining her backgrounds in agriculture and the geological sciences. Becky raises sheep and operates a fiber-processing mill on the ranch that she has been operating with her husband for 30 yr. She has worked as a geologist/geochemist in the environmental consulting industry in Montana, Colorado, and Utah, and in a research capacity in Antarctica and Greenland. Her degrees are in the geological sciences from Harvard University (BA) and the University of Maine (MS). She has served on the Montana Board of Livestock and on the Conservation and Science Board for Lava Lake Land and Livestock.

Cathy Whitlock is Professor of Earth Sciences, Fellow, and former co-Director of the Montana Institute on Ecosystems. She is recognized nationally and internationally for her scholarly contributions and leadership activities in the areas of paleoecology and paleoclimate. Whitlock has published over 180 scientific papers on these topics and her research has been supported by grant-funding from the National Science Foundation, Joint Fire Sciences Program, National Park Service, USDA Forest Service, and Department of Energy. She is a Fellow of the American Association for the Advancement of Science and the Geological Society of America and received the international EO Wilson Biodiversity Technology Pioneer Award in 2014 and Professional Excellence Award in Academic/Research, Association of Women Geoscientists in 2015.

BACK COVER

Late May snows, Bridger Canyon near Bozeman.
Photograph courtesy of Scott Bischke.



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