DRAFT Climate Change in Montana

Colin Brust

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Draft Overview

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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 residents of Montana 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 average temperature increase between 1951 and 2015 across Montana was 1.92°F

Winter and spring in Montana have experienced the most warming. Average temperatures during these seasons have risen by 3.4°F between 1950 and 2015.

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.

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 0.96 inches, 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 (1.34-1.98 inches) has also occurred during this period for the eastern portion of the state.

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 3.6-5.5°F depending on the emission scenario. By the end-of-century, Montana temperatures are projected to increase 3.7-9.2°F depending on the emission scenario. T

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.

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 eastern parts of the state.

Climate Change Defined

The US Global Change Research Program ([1]) 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."

Outline

This document 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.

1 Draft 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.

> 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.

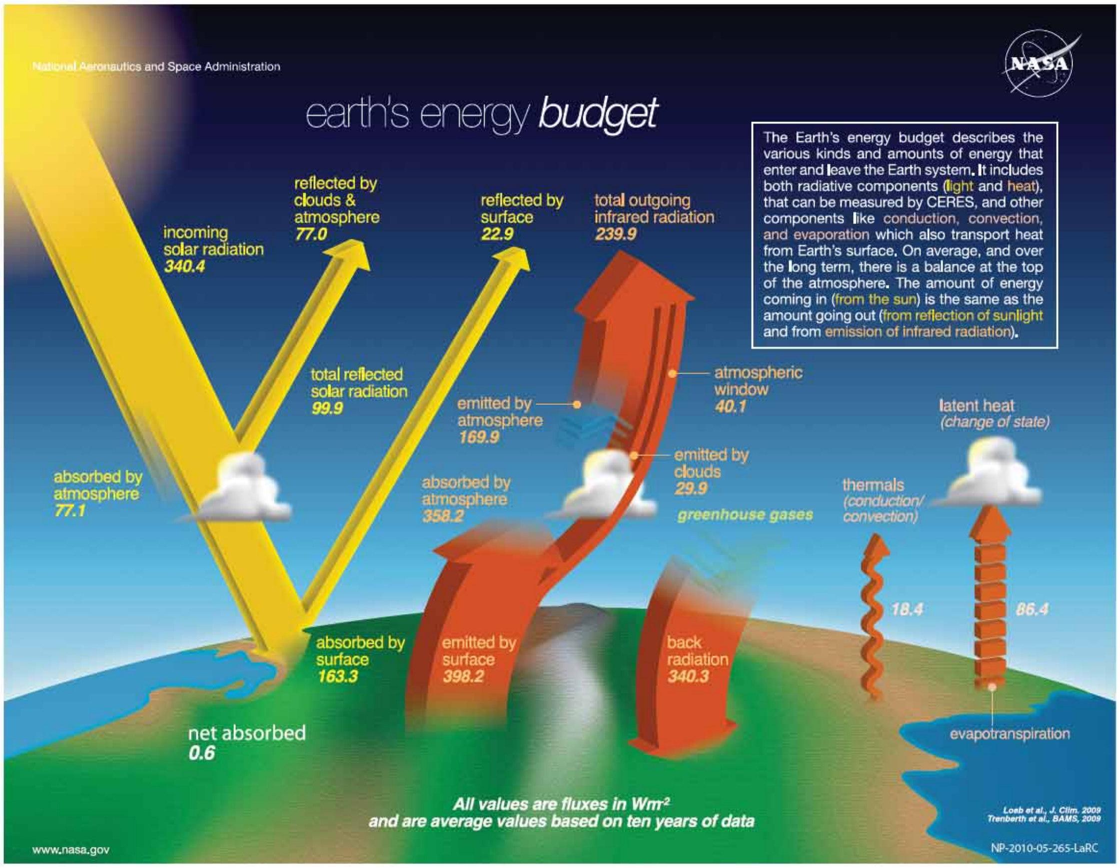

Figure 1.1: The Earth's radiation balance is the main driver of our climate. Image courtesy of National Aeronautics and Space Administration ([2])

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 (CO2), methane (CH4), nitrous oxide (N2O), water vapor (H2O), and ozone (O3).

Incoming solar radiation is either absorbed, reflected, or re-radiated from the Earth's surface.

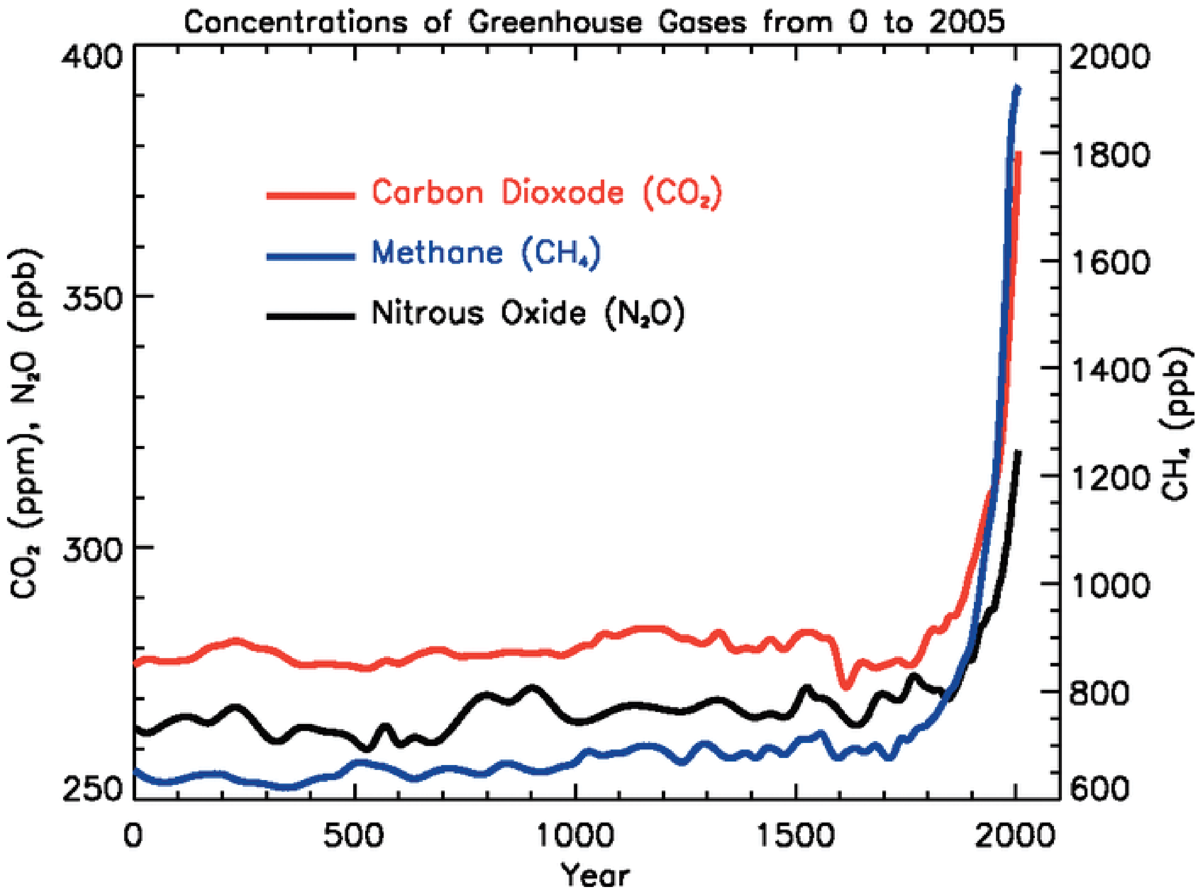

Figure 1.2: Changes in important global atmospheric greenhouse gas concentrations from year 0 to 2005 AD (ppm, ppb = parts per million and parts per billion, respectively) (Forster et al. 2007).

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 1.2), 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.

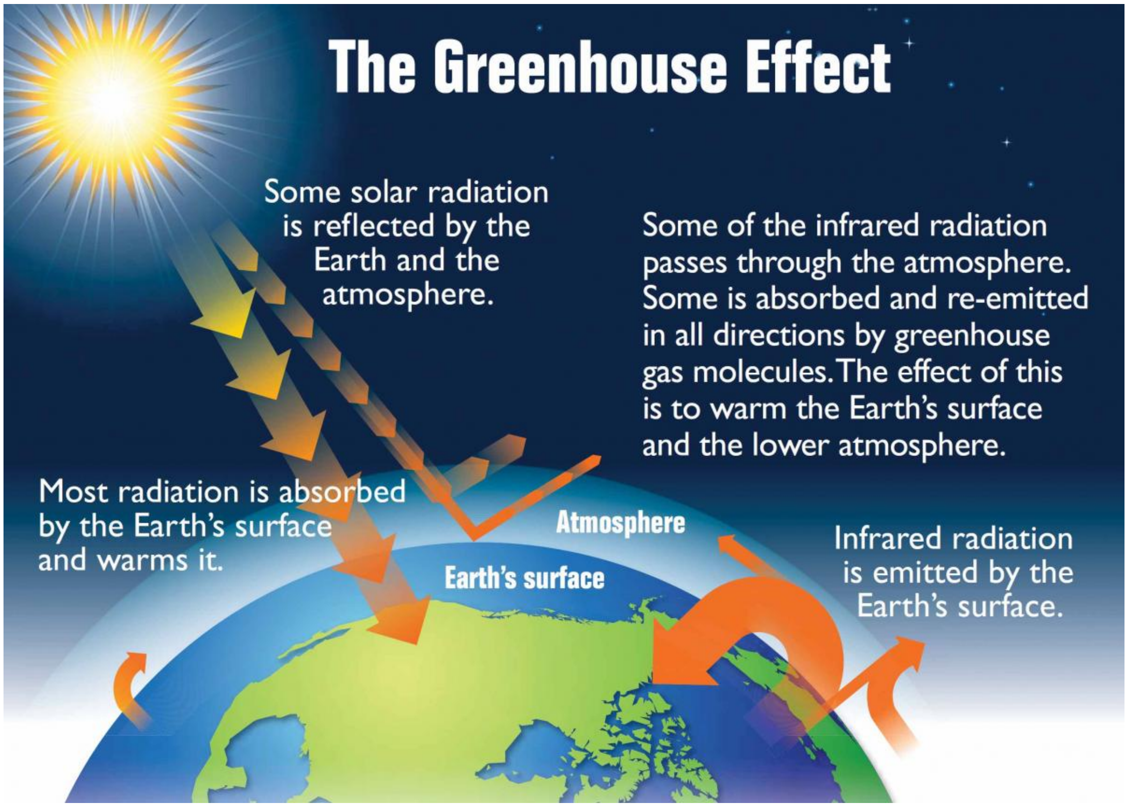

Figure 1.3: Climate change occurs when the Earth's energy budget is not in balance. Such change generally takes place over centuries and millennia. Human-caused climate change has been occurring over the last 200 yr, largely because of the combustion of fossil fuels and subsequent increase of atmospheric CO2. Carbon dioxide, as well as CH4 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).

2 Draft 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.

Figure 2.1: The IPCC

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.

3 Draft Historical Climate

3.1 Climate Conditions 1981 - 2020

To assess Montana's current climate, we analyzed climate variable data (see sidebar) provided as 3-decade of gridMET climate data[3]. In this section, we review average temperature and precipitation conditions from 1981-2010 as an indicator of current climate conditions.

> Climate Variables
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> 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.

3.1.1 Temperature

Table 3.1 shows the average seasonal temperature variation across Montana's 7 Climate Divisions from 1981-2010. Temperatures vary across Montana, with average annual values ranging from 29.1°F to 47.4°F across the region.

Table 3.1: Average (minimum / average / maximum) temperatures (°F) for the seven Montana climate divisions from 1981-2010.

Division	Winter	Spring	Summer	Fall
Central	16.8 / 27.6 / 38.5	37.2 / 49.9 / 62.5	46.7 / 61.5 / 76.3	22 / 32.8 / 43.6
North Central	13.6 / 24.8 / 36.1	38.2 / 51.3 / 64.4	47.2 / 62.2 / 77.2	19.8 / 31.2 / 42.5
Northeastern	10.7 / 21.7 / 32.8	39.9 / 53.5 / 67	49.9 / 64.9 / 79.9	18.3 / 29.7 / 41.1
South Central	17.1 / 28 / 38.9	38 / 50.7 / 63.4	48 / 62.8 / 77.5	22.2 / 33 / 43.8
Southeastern	14.3 / 26.1 / 37.9	40.4 / 54 / 67.5	50.9 / 66.4 / 81.8	20.3 / 32.5 / 44.7
Southwestern	15 / 24.5 / 34.1	33.1 / 45 / 56.9	42.9 / 57.1 / 71.4	19.6 / 29 / 38.4
Western	19 / 27.2 / 35.5	35.2 / 47 / 58.9	43.9 / 58 / 72.2	23 / 30.7 / 38.3

Seasonal temperatures across Montana vary, with seasonal average Winter, Spring, Summer and Fall temperatures of 25.7°F, 50.3°F, 61.9°F, and 31.3°F, respectively.

3.1.2 Precipitation

Table 3.2 shows the seasonal variation of precipitation across Montana's 7 Climate Divisions from 1981-2010. The average annual precipitation for Montana is 19.2.

Table 3.2: Average precipitation in inches for the seven Montana climate divisions from 1981-2010.

Division	Winter	Spring	Summer	Fall
Central	2.7	7.6	4.7	3.1
North Central	2.1	6.4	4.3	2.4
Northeastern	1.2	5.9	4.6	1.8
South Central	3.1	7.3	4.1	3.6
Southeastern	1.6	6.5	4.2	2.2
Southwestern	4.7	8.2	4.6	4.9
Western	8.9	8.8	4.9	9.5

3.2 Historical Trends 1951 - Present

We evaluated how temperature and precipitation have historically changed, dating back to 1950. 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 Montana has 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.

The presentation of trends that follows is confined to the period from 1950–2015 using data from NOAA's NClimGrid Dataset ([4]). This is widely acknowledged as the benchmark period in climate analysis ([5]), a period when our network of meteorological sensors becomes more accurate and sufficiently dense.

3.2.1 Temperature

Table 3.3 shows the decadal rate of change from 1950-2015 for average annual temperatures across Montana 7 Climate Divisions. We provide that rate of change both annually and by season for Montana. We also present the average annual and average seasonal changes across the region. To account partially for autocorrelation we considered trends as significant with a conservative p value at $p<0.05$.

Table 3.3: Decadal rate of change for annual average temperatures in °F (°C) for each region in the study area from 1950-2015. A value of 0 indicates no statistically significant change between decadal averages.

Division	Annual	Winter	Spring	Summer	Fall
Central	0.31	0.50	0.56	0.26	0.24
North Central	0.35	0.70	0.58	0.27	0.24
Northeastern	0.29	0.61	0.58	0.22	0.21
South Central	0.33	0.44	0.58	0.33	0.30
Southeastern	0.26	0.52	0.51	0.17	0.24
Southwestern	0.26	0.27	0.57	0.27	0.24
Western	0.30	0.33	0.47	0.38	0.30
Statewide	0.30	0.50	0.55	0.27	0.25

The rate of temperature change across Montana was 0.3°F/decade (Table 3.3). Across Climate Divisions average annual minimum and maximum temperature changes ranged from 0.18-0.16°F/decade, respectively. Between 1950 and 2015, Montana's average annual temperature has increased by 1.92°F; annual maximum and minimum temperatures have increased by approximately 1.15°F and 1.02°F, respectively.

3.2.2 Precipitation

Table 3.4 shows the decadal rate of change from 1950-2015 for average total precipitation across Montana 7 Climate Divisions. We provide that rate of change both annually and by

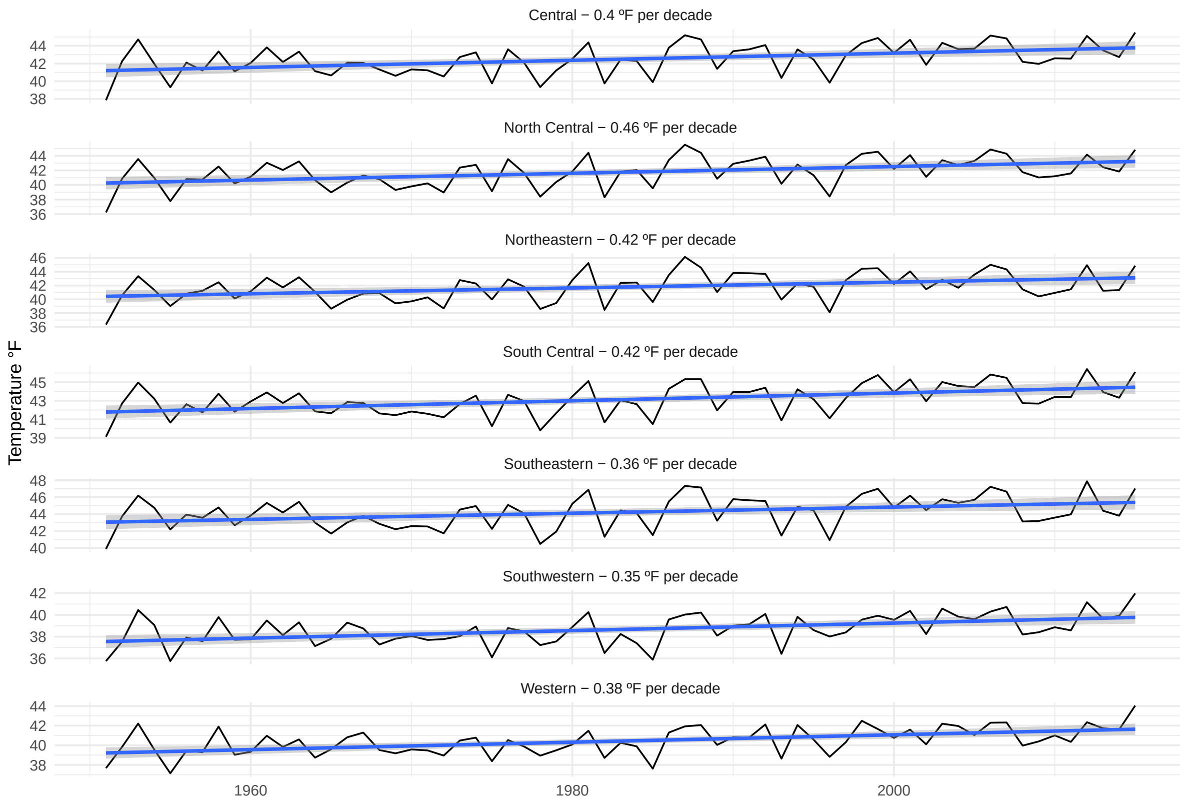

Figure 3.1: Trends in annual average temperature across each Climate Division in Montana

season for Montana. We also present the average annual and average seasonal changes across the region. To account partially for autocorrelation we considered trends as significant with a conservative p-value at $p<0.05$.

Table 3.4: Decadal rate of change in average precipitation in inches/decade for the seven Montana climate divisions from 1951-2015. A value of 0 indicates no significant change.

Division	Annual	Winter	Spring	Summer	Fall
Central	0.00	-0.12	0.08	0	0.06
North Central	0.00	-0.09	0.08	0	0.09
Northeastern	0.36	0.00	0.21	0	0.07
South Central	0.00	0.00	0.09	0	0.07
Southeastern	0.37	0.00	0.31	0	0.09
Southwestern	0.00	-0.13	0.09	0	0.07
Western	-0.36	-0.56	0.00	0	0.00
Statewide	0.00	-0.15	0.13	0	0.06

The rate of precipitation change across Montana was 0in./decade (Table 3.4). Between 1950 and 2015, Montana's average annual precipitation has not changed by 0 inches.

3.2.3 Extreme aspects of Montana's climate IN PROGRESS

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.

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).

extremes table

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.

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4 Draft 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. 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.

4.1 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 4.1). 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 (Figure 4.1 and Figure 4.2) (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.

4.2 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), and precipitation is decreased (Figure 4.3). Effects during the cool phase reverse, with cooler winter temperatures and increased precipitation experienced over western North America.

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.

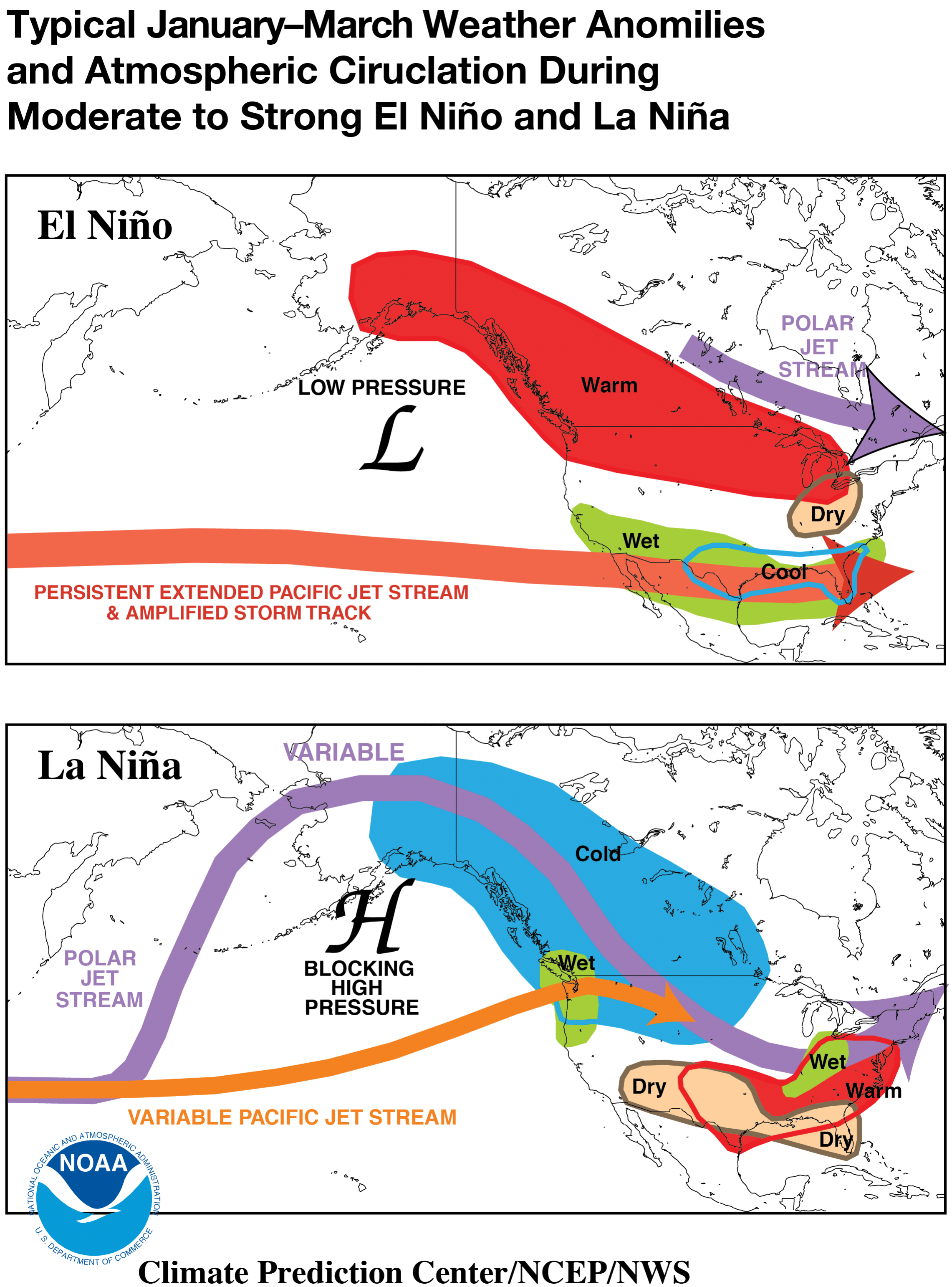

Figure 4.1: Typical January-March weather anomalies and atmospheric circulation during El Niño (top) and La Niña (bottom) events. Image courtesy National Weather Service (NWSa undated).

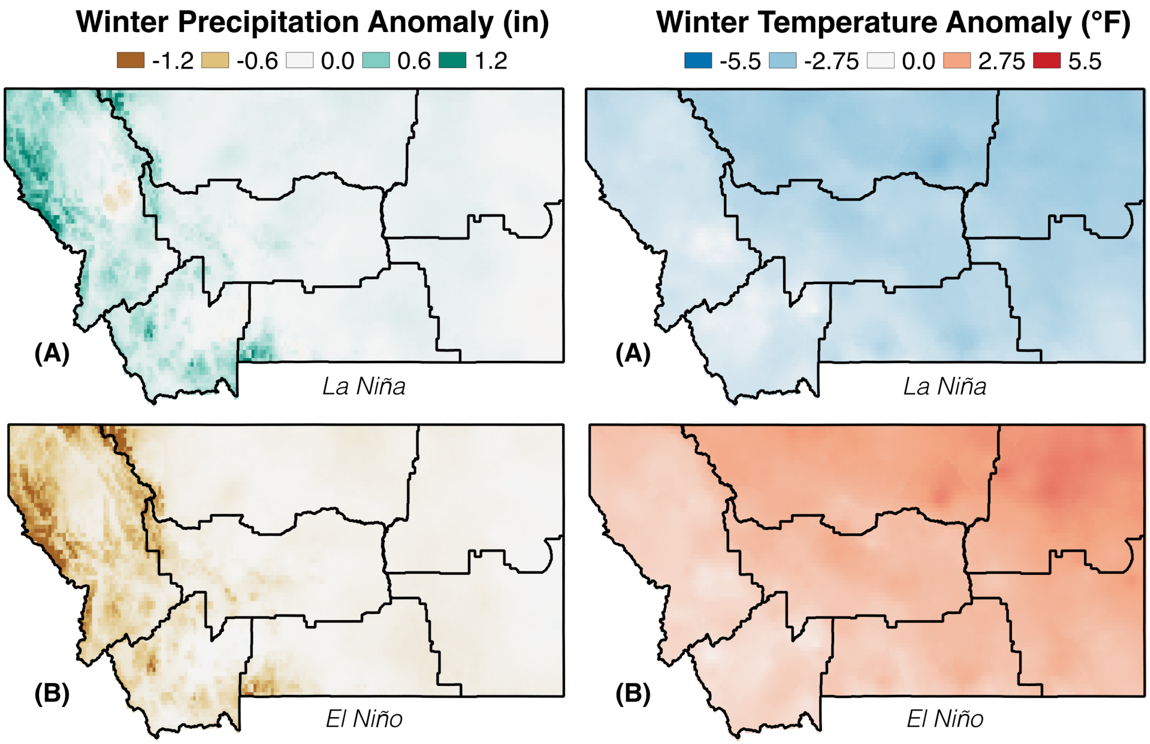

Figure 4.2: (A) Top two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during La Niña events. (B) Bottom two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during El Niño events. For Montana, El Niño winters 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.

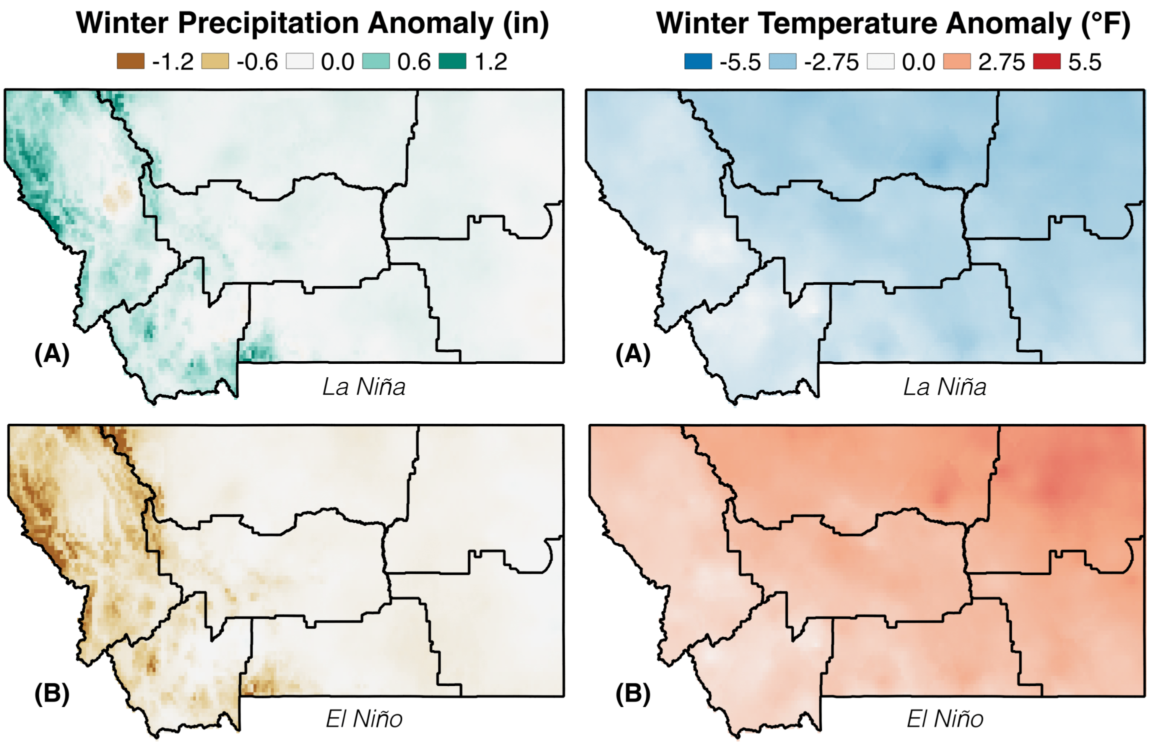

Figure 4.3: (A) Top two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during the cool phase of the Pacific Decadal Oscillation. (B) Bottom two images show the average anomaly in Montana's winter precipitation (left) and temperature (right) during the 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.

5 Draft Future Projections

5.1 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. 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.

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 sixth iteration of the Coupled Model Intercomparison Project (CMIP6), which includes over 100 GCMs depending on the experiment conducted ([6]). The World Climate Research Program describes CMIP as "a standard experimental protocol for studying the output" of GCMs ([7]). It provides a means of validating, comparing, documenting, and accessing diverse climate model results. The CMIP project dates back to 1995, with the sixth iteration (CMIP6) starting in 2016 and providing climate data for the latest IPCC Sixth Assessment Report ([8]).

We employed 8 individual GCMs from the CMIP6 project for the Montana Climate Assessment ensemble, chosen because they provide daily outputs and are found to have a realistic performance over North America ([9])

The benefits of using CMIP6 data are that each model in the ensemble a) has been rigorously evaluated, and b) uses the same standard socioeconomic trajectories—known as Shared Socioeconomic Pathways (SSPs)—to describe future greenhouse gas emissions. "The SSPs are based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development" ([10])

Shared Socioeconomic Pathways

There are five different SSP categories that climate projections are grouped by (following text taken from[10]): - SSP1 Sustainability: Taking the Green Road (Low challenges to mitigation and adaptation) The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

- SSP2 Middle of the Road: (Medium challenges to mitigation and adaptation) The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

- SSP3 Regional Rivalry: A Rocky Road (High challenges to mitigation and adaptation) A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

- SSP4 Inequality: A Road Divided (Low challenges to mitigation, high challenges to adaptation) Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

- SSP5 Fossil-fueled Development: Taking the Highway (High challenges to mitigation, low challenges to adaptation) This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological

> progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

For the Montana Climate Assessment, we explore the SSP1, SSP2, SSP3, and SSP5 scenarios.

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. 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 8 downscaled GCMs in CMIP6 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 (1981–2010) 30-year average, which results in a projected difference, or change, from historical conditions. We make those projections using the stabilization the four SSPs outlined above. 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.

5.2 Summary of Projections

5.2.1 Temperature 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 all SSP scenarios, with the lower consequence scenarios showing lower magnitudes of change than the more extreme.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.

5.2.2 Precipitation 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 slight increases in both the annual number of consecutive dry and wet days. Overall, the differences in precipitation resulting from the different emission scenarios 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 more extreme emission scenarios.

5.3 Temperature Projections

Below we provide projections for various aspects of Montana's future temperature based on our modeling analysis.

We discuss a subset of our modeling results here, including a) temperature projections reported by the mean values of the 8 GCM ensemble and b) figures that include maps and graphs that represent the mean value and distribution of values observed for temperature across the 8 GCMs.

We also report a percent agreement of the 8 GCMs used for the analysis. The percent agreement represents the number of GCMs that project the same sign of change (i.e., positive or negative) as the mean value. For example, if the mean value is positive and 7 out of 8 models also project positive change, then the percent agreement would be 100 x 7/8 = 87.5%. This simple calculation helps convey the uncertainty in the projections.

5.3.1 Average Annual Temperatures

Figure 5.1 shows projected changes in average annual temperatures across all Climate Divisions for both the mid- and end-of-century. Below, projected changes in average annual temperature across the domain and associated model agreements are given:

- Mid-century: Across the domain, the majority of SSP scenarios project that the average annual temperature in the mid-century will increase. Changes in average annual temperature across SSPs range from 3.6 °F (100% model agreement) to 5.48 °F (100% model agreement)
- End-of-century: Across the domain, the majority of SSP scenarios project that the average annual temperature in the end-of-century will increase. Changes in average annual temperature across SSPs range from 3.65 °F (100% model agreement) to 9.23 °F (100% model agreement)

5.3.2 Average Daily Minimum Temperatures

Figure 5.2 shows spatially distributed changes in minimum annual temperature across all Climate Divisions for both the mid- and end-of-century. Below, projected changes in both minimum temperature and associated model agreements are given for the entire domain:

- Mid-century: Across the domain, the majority of SSP scenarios project that the average annual minimum temperature in the mid-century will increase. Changes in average annual minimum temperature across SSPs range from 3.54 °F (100% model agreement) to 5.53 °F (100% model agreement)
- End-of-century: Across the domain, the majority of SSP scenarios project that the average annual minimum temperature in the end-of-century will increase. Changes in average annual minimum temperature across SSPs range from 3.51 °F (100% model agreement) to 9.34 °F (100% model agreement)

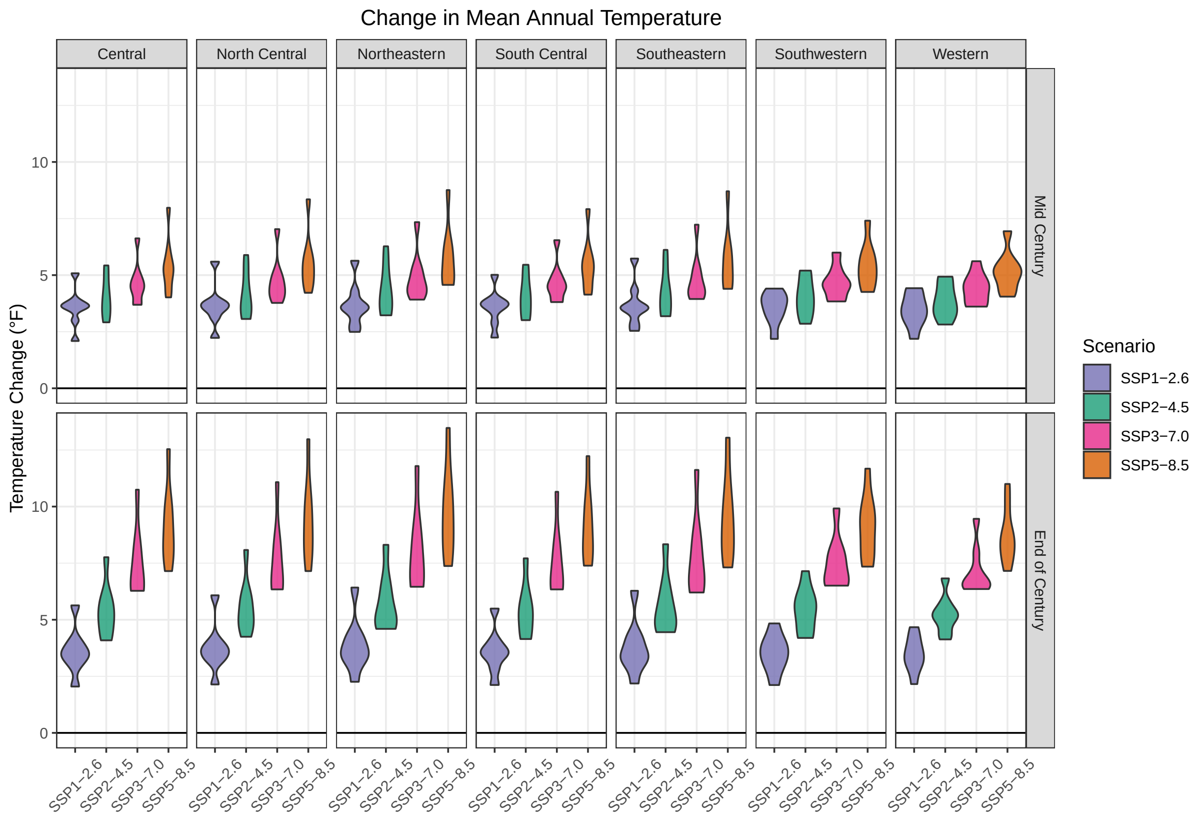

Figure 5.1: Graphs showing the distribution of projected changes in temperature (°F) projected for each Climate Division across all SSP scenarios. The top row shows mid-century (2040-2069) projections and the bottom row shows end-of-century (2070-2099) projections.

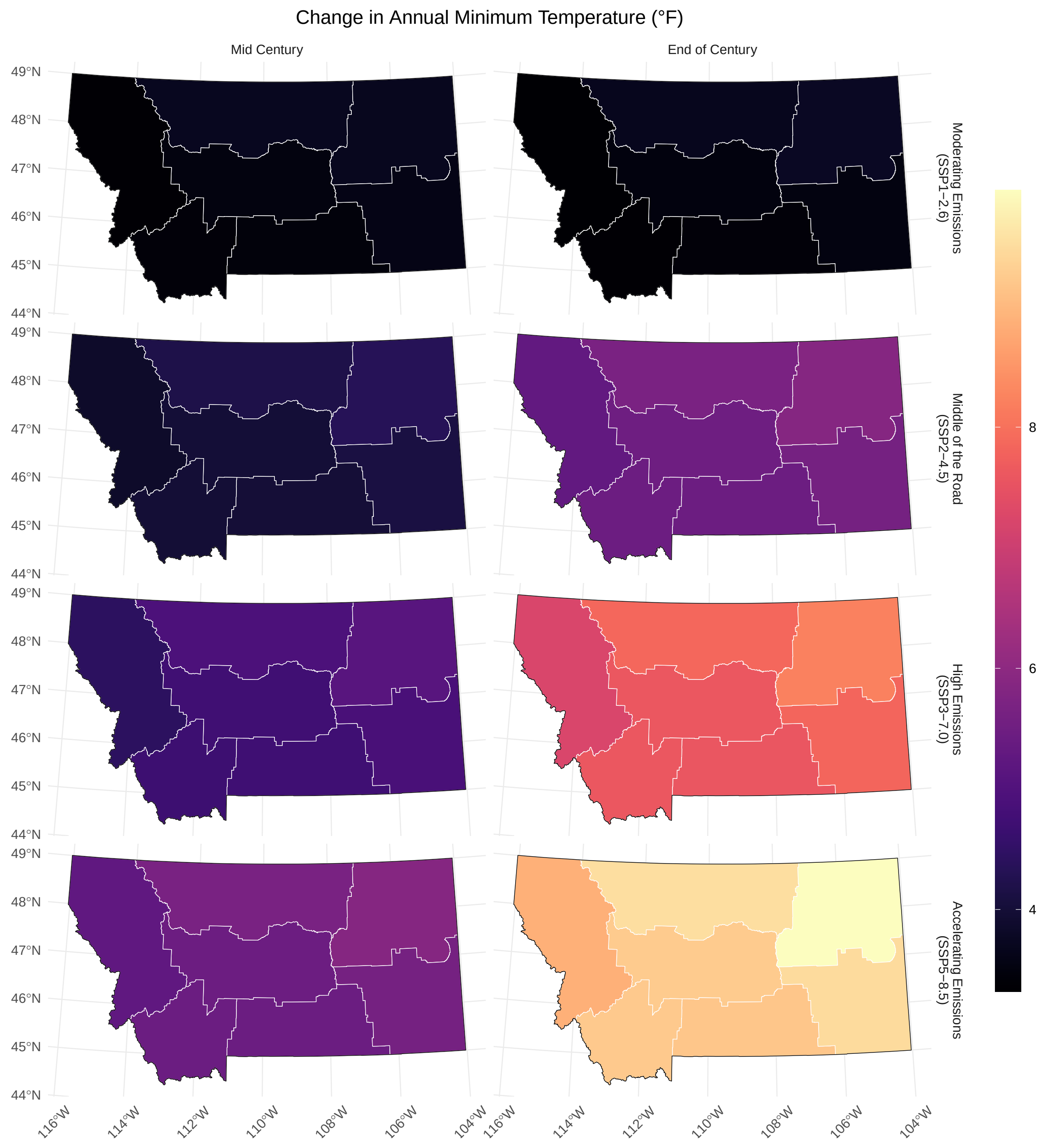

Figure 5.2: The projected increase in annual average daily minimum temperature (°F) for each Climate Division in Montana for the periods 2049-2069 and 2070-2099 for all SSP scenarios

5.3.3 Average Daily Maximum Temperatures

Figure 5.3 shows spatially distributed changes in maximum annual temperature across all Climate Divisions for both the mid- and end-of-century. Below, projected changes in both maxiimum temperature and associated model agreements are given for the entire domain:

- Mid-century: Across the domain, the majority of SSP scenarios project that the average annual maximum temperature in the mid-century will increase. Changes in average annual maximum temperature across SSPs range from 3.66 °F (100% model agreement) to 5.43 °F (100% model agreement)

- End-of-century: Across the domain, the majority of SSP scenarios project that the average annual maximum temperature in the end-of-century will increase. Changes in average annual maximum temperature across SSPs range from 3.78 °F (100% model agreement) to 9.12 °F (100% model agreement)

5.3.4 Average Monthly Temperatures

Figure 5.4 shows projected changes in average monthly temperatures across all Climate Divisions for both the mid- and end-of-century. Below, projected changes in average monthly temperature across the domain and associated model agreements are given:

- Mid Century: Average Temperature is projected to increase in the Winter, with values ranging from 3.47 °F to 5.22 °F (100% model agreement) depending on the SSP scenario. Average Temperature is projected to increase in the Spring, with values ranging from 3.29 °F to 4.5 °F (100% model agreement) depending on the SSP scenario. Average Temperature is projected to increase in the Summer, with values ranging from 3.65 °F to 6.23 °F (100% model agreement) depending on the SSP scenario. Average Temperature is projected to increase in the Fall, with values ranging from 3.99 °F to 5.99 °F (100% model agreement) depending on the SSP scenario.

- End of Century: Average Temperature is projected to increase in the Winter, with values ranging from 3.22 °F to 8.67 °F (99% model agreement) depending on the SSP scenario. Average Temperature is projected to increase in the Spring, with values ranging from 3.17 °F to 7.39 °F (100% model agreement) depending on the SSP scenario. Average Temperature is projected to increase in the Summer, with values ranging from 4.14 °F to 10.88 °F (100% model agreement) depending on the SSP scenario. Average Temperature is projected to increase in the Fall, with values ranging from 4.06 °F to 10.02 °F (100% model agreement) depending on the SSP scenario.

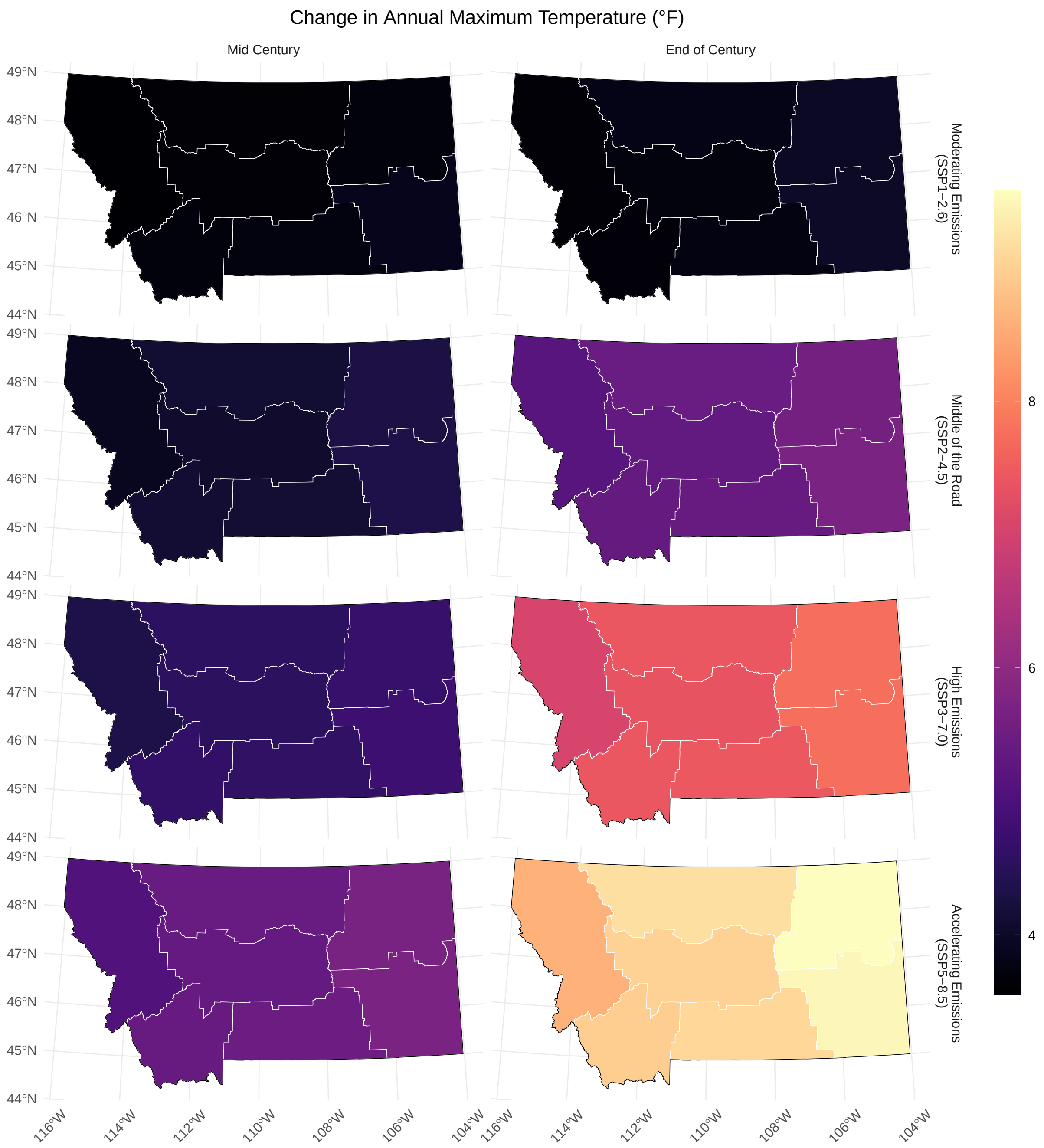

Figure 5.3: The projected increase in annual average daily maximum temperature (°F) for each Climate Division in Montana for the periods 2049-2069 and 2070-2099 for all SSP scenarios

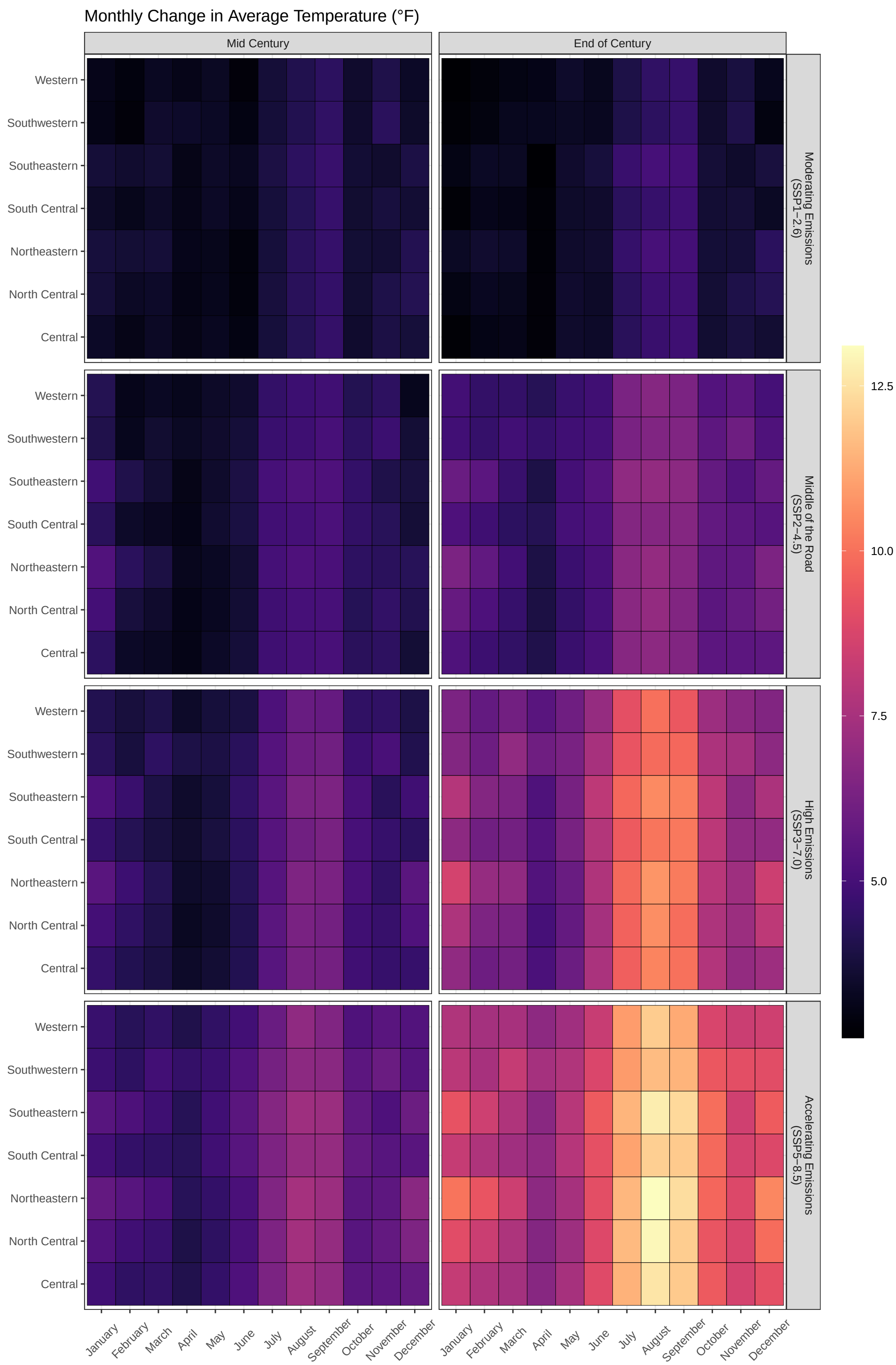

Figure 5.4: The projected monthly increase in average temperature (°F) for each Climate Division in Montana in the mid-century (2040-2069) and end-of century (2070 - 2099) for all SSP scenarios

5.3.5 Number of Days Above 90°F (32°C)

Figure 5.5 and Figure 5.6 show projected changes in number of days above 90°F for both the mid- and end-of-century. Below, projected changes in days above 90°F across the domain and associated model agreements are given:

- Mid-century: Across the domain, the majority of SSP scenarios project that the number of days above 90°F in the mid-century will increase. Changes in number of days above 90°F across SSPs range from 14.16 days (100% model agreement) to 26.85 days (100% model agreement)

- End-of-century: Across the domain, the majority of SSP scenarios project that the number of days above 90°F in the end-of-century will increase. Changes in number of days above 90°F across SSPs range from 17.35 days (100% model agreement) to 48.97 days (100% model agreement)

5.3.6 Number of Days Where Minimum Temperatures are Above 32°F (0°C)

Figure 5.7 and Figure 5.8 show projected changes in number of days freeze-free days for both the mid- and end-of-century. Below, projected changes in the number of freeze-free days across the domain and associated model agreements are given:

- Mid-century: Across the domain, the majority of SSP scenarios project that the number of freeze-free days in the mid-century will increase. Changes in number of freeze-free days across SSPs range from 22.29 days (100% model agreement) to 32.1 days (100% model agreement)

- End-of-century: Across the domain, the majority of SSP scenarios project that the number of freeze-free days in the end-of-century will increase. Changes in number of freeze-free days across SSPs range from 21.02 days (100% model agreement) to 55.11 days (100% model agreement)

5.3.7 Summary

Talk with team about how to summarize

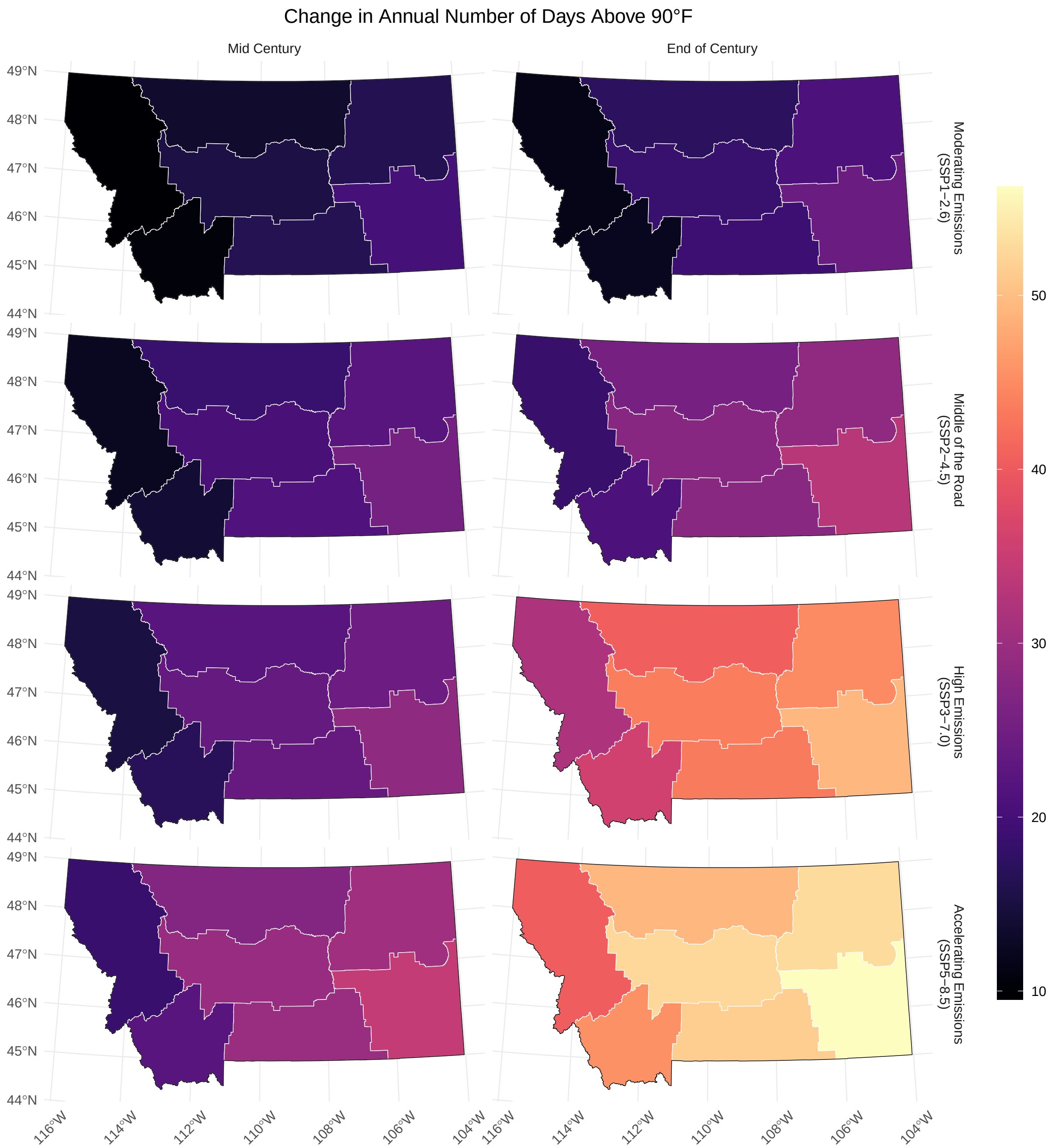

Figure 5.5: The projected increases in number of days above 90°F (32°C) for each Climate Division in Montana over two periods 2040-2069 and 2070-2099 for all SSP scenarios

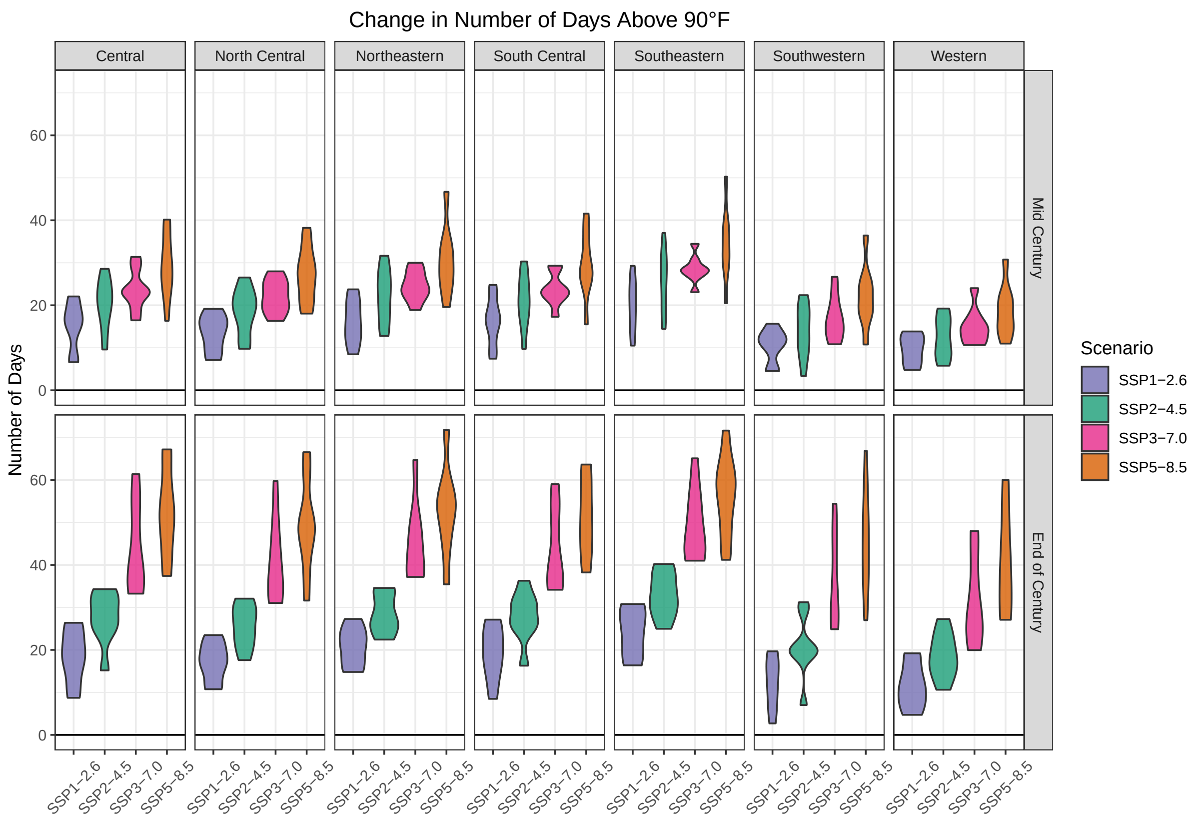

Figure 5.6: Graphs showing the distribution across ensemble members of the increase in number of days per year above 90°F (32°C) projected for each Climate Division all SSP scenarios and both mid-century (2040-2069) and end-of-century (2070-2099) projections.

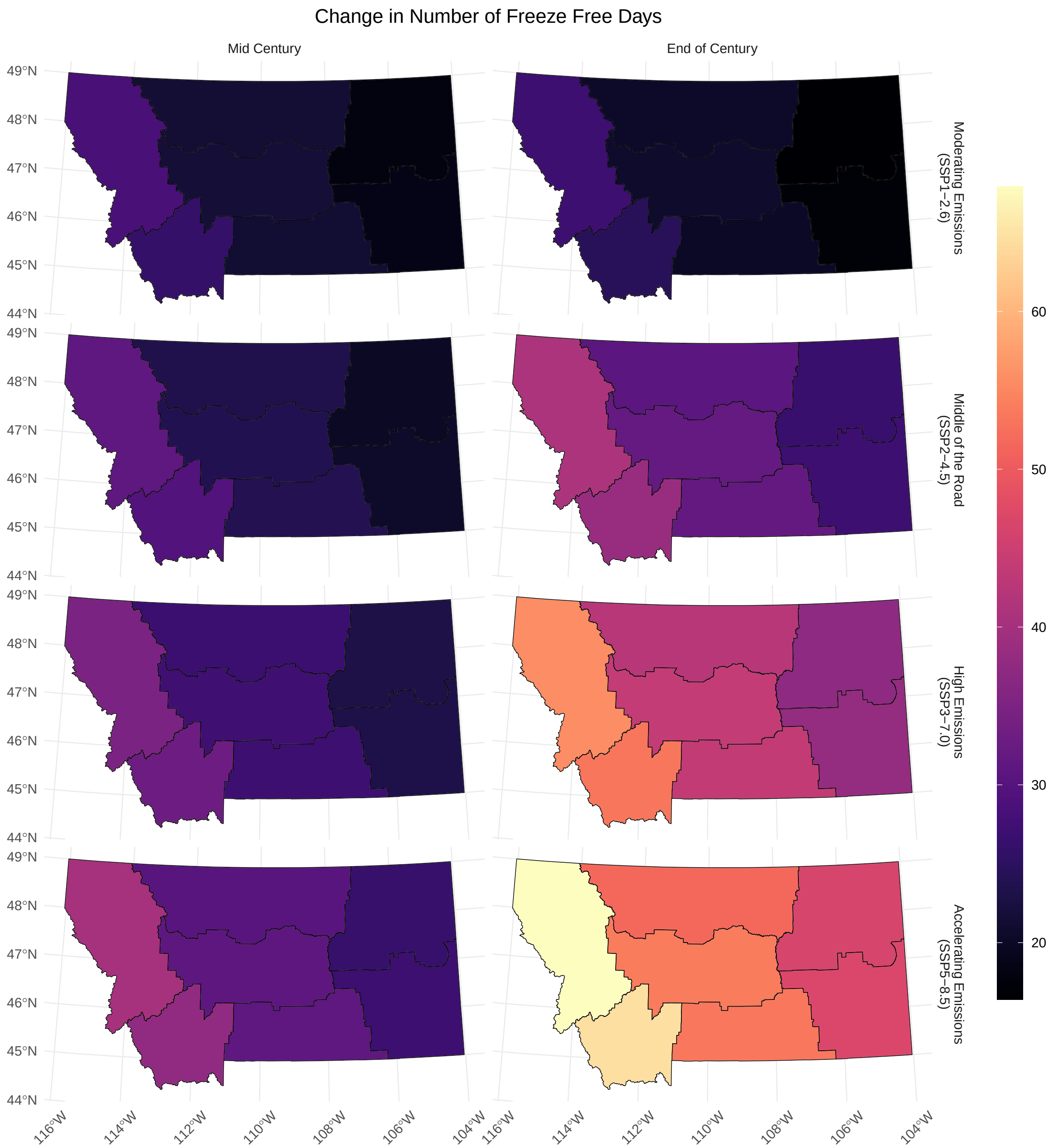

Figure 5.7: The projected change in the number of frost-free days for each Climate Division in Montana over two periods 2040-2069 and 2070-2099 for all SSP scenarios.

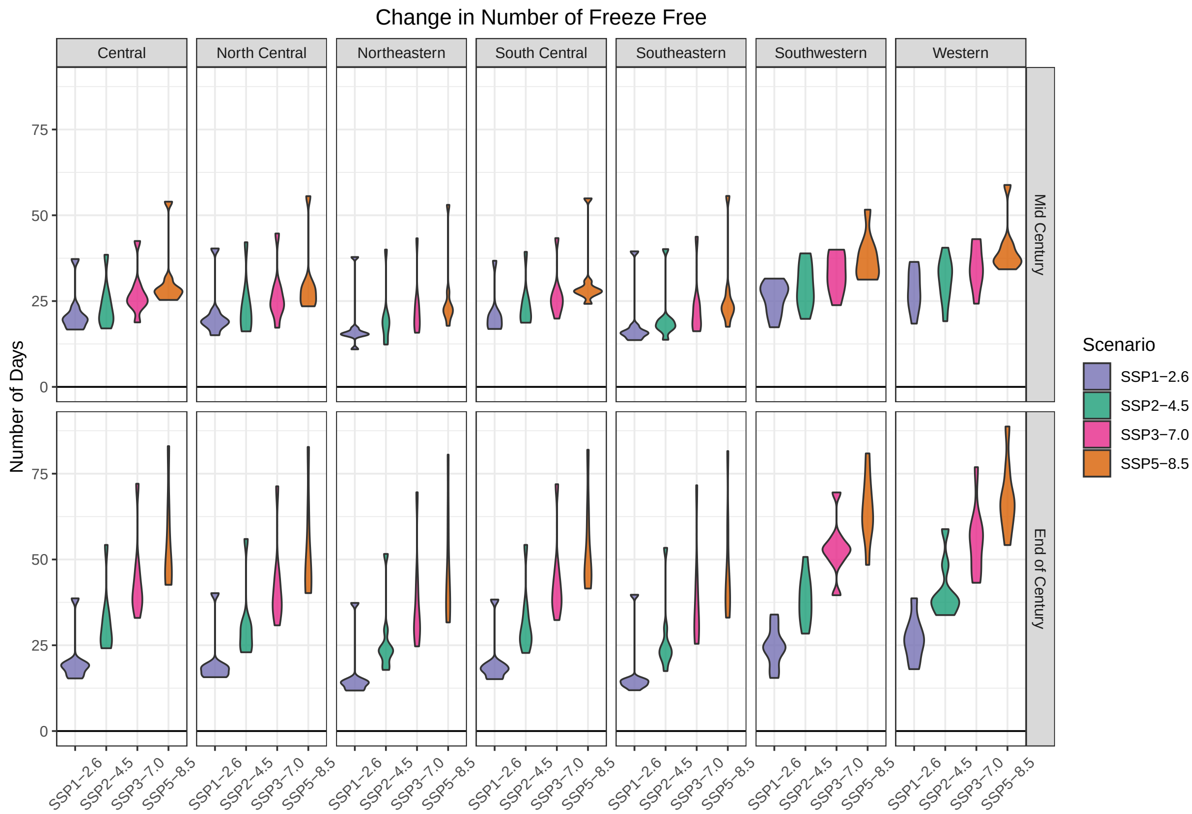

Figure 5.8: Graphs showing the increases in frost-free days/yr projected for each Climate Division across all SSP scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099).

5.4 Precipitation Projections

Below we provide projections of Montana's future precipitation based on our modeling efforts. Those projections cover all SSP scenarios and 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 mean values of the 8 GCM ensemble and b) figures that include maps and graphs that represent the mean and distribution of values observed for precipitation across the 8 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, mean values do not characterize the potential for spatial variability that exists within these regions.

5.4.1 Average Annual Precipitation

Figure 5.9 and Figure 5.10 show projected changes in annual total precipitation for both the mid- and end-of-century. Below, projected changes in total annual precipitation across the domain and associated model agreements are given:

- Mid-century: Across the domain, the majority of SSP scenarios project that the total annual precipitation in the mid-century will increase. Changes in total annual precipitation across SSPs range from 0.99 inches (75% model agreement) to 1.3 inches (88% model agreement)
- End-of-century: Across the domain, the majority of SSP scenarios project that the total annual precipitation in the end-of-century will increase. Changes in total annual precipitation across SSPs range from 1.06 inches (88% model agreement) to 1.46 inches (88% model agreement)

5.4.2 Interannual Variability

Interannual variability (i.e., the amount precipitation changes from year to year) is projected to increase across the domain by mid century and increase by the end-of-century for the majority of SSP scenarios (Figure 5.11). These changes could be attributed to wet years getting wetter, dry years getting drier, or some combination of both.

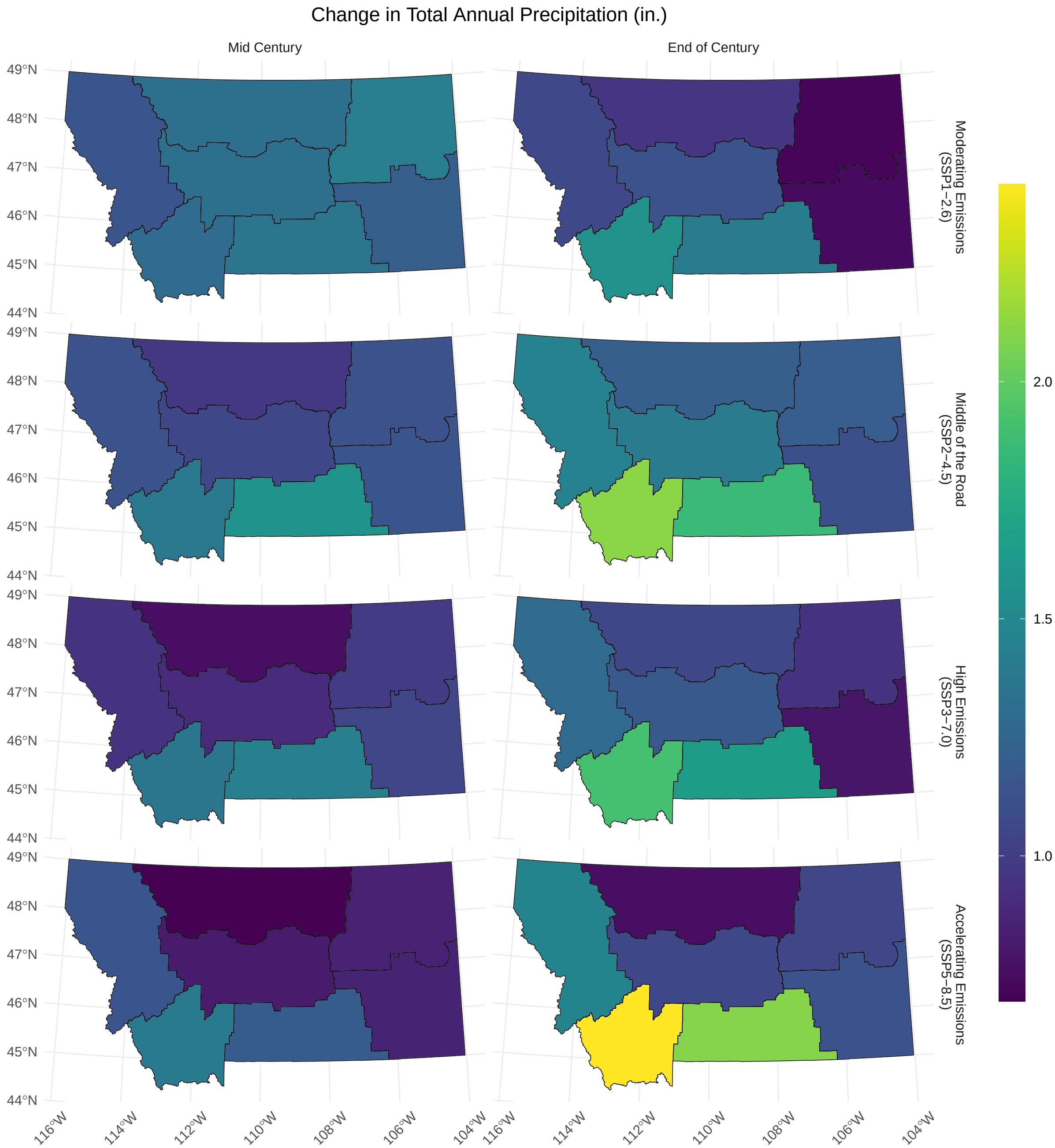

Figure 5.9: The projected change in annual precipitation (inches) for each Climate Division in Montana over two periods 2040-2069 and 2070-2099 for all SSP scenarios.

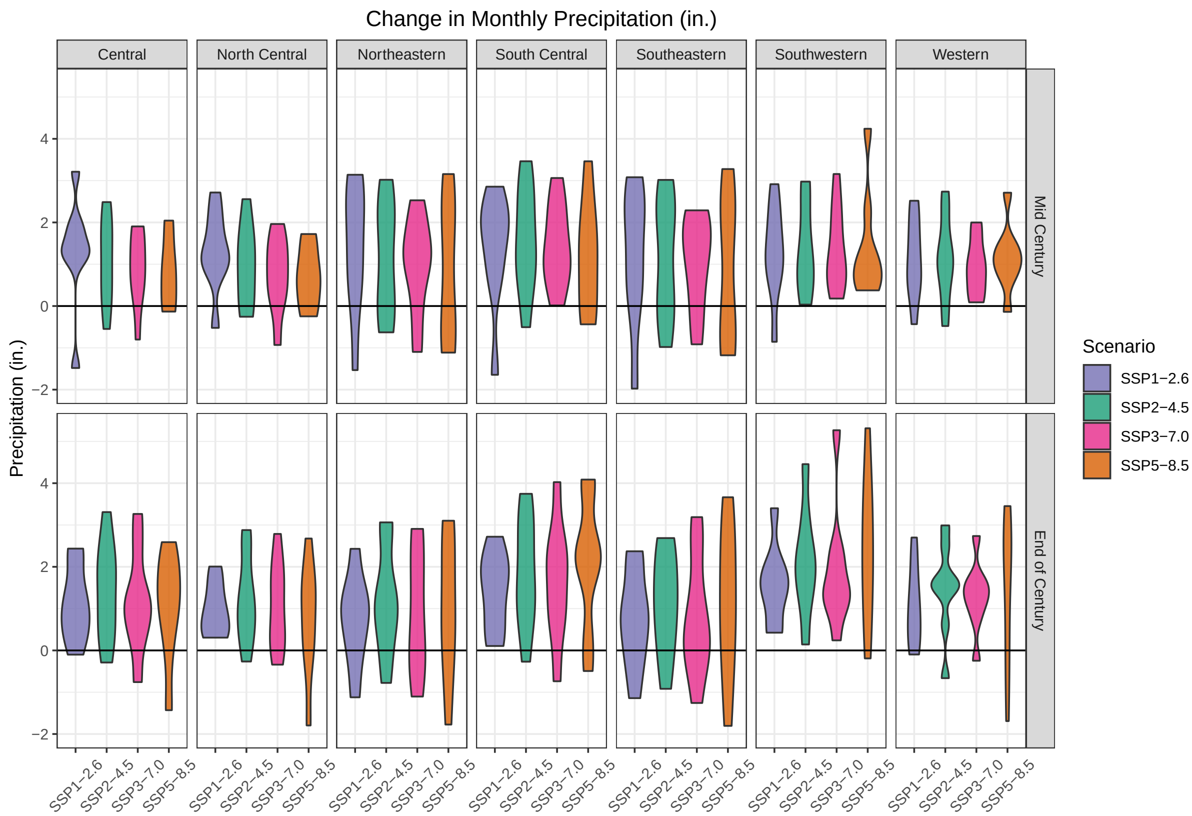

Figure 5.10: Graphs showing annual precipitation change (in inches) projected for each Climate Division for all SSP scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099).

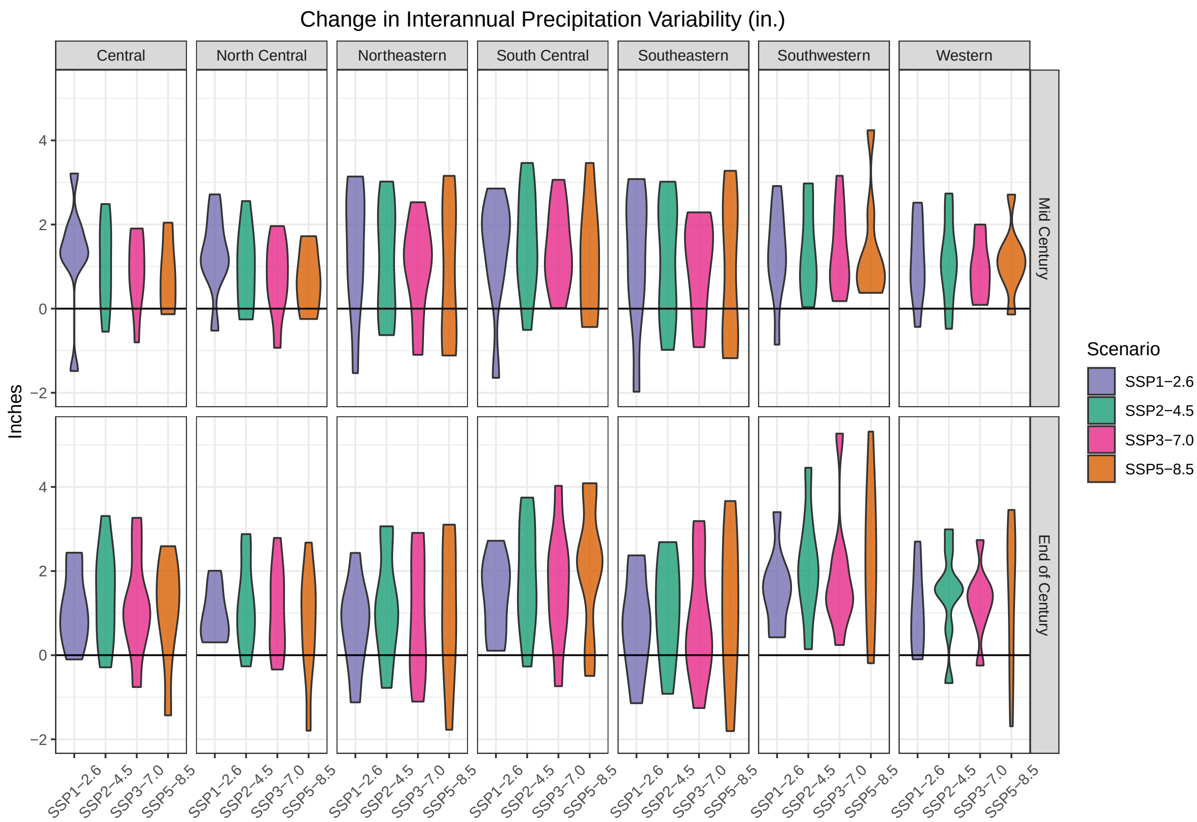

Figure 5.11: Graphs showing the interannual variability of precipitation projected for each Climate Division for all SSP scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows for end-of-century projections (2070-2099).

5.4.3 Monthly and Seasonal Change in Average Precipitation

Figure 5.12 shows projected changes in average monthly precipitation across all Climate Divisions for both the mid- and end-of-century. Below, projected changes in average monthly precipitation across the domain and associated model agreements are given:

- Mid Century: Total Precipitation is projected to increase in the Winter, with values ranging from 0.06 inches to 0.1 inches (77% model agreement) depending on the SSP scenario. Total Precipitation is projected to increase in the Spring, with values ranging from 0.25 inches to 0.3 inches (91% model agreement) depending on the SSP scenario. Total Precipitation is projected to decrease in the Summer, with values ranging from -0.05 inches to 0.07 inches (65% model agreement) depending on the SSP scenario. Total Precipitation is projected to increase in the Fall, with values ranging from 0.01 inches to 0.06 inches (67% model agreement) depending on the SSP scenario.

- End of Century: Total Precipitation is projected to increase in the Winter, with values ranging from 0.05 inches to 0.17 inches (82% model agreement) depending on the SSP scenario. Total Precipitation is projected to increase in the Spring, with values ranging from 0.23 inches to 0.42 inches (90% model agreement) depending on the SSP scenario. Total Precipitation is projected to decrease in the Summer, with values ranging from -0.2 inches to 0.04 inches (67% model agreement) depending on the SSP scenario. Total Precipitation is projected to increase in the Fall, with values ranging from 0.03 inches to 0.09 inches (74% model agreement) depending on the SSP scenario.

5.4.4 Projected Changes 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. Across the domain, we found a increase in consecutive dry days for the mid-century across the all SSPs (65.25% agreement) and a increase in consecutive dry days for the end-of-century across the all SSPs (75% agreement). Figures Figure 5.13 and Figure 5.14 show changes in projected number of dry days across Climate Divisions and domain-wide projections for mid- and end-of-century are given below:

- Mid-century: Across the domain, the majority of SSP scenarios project that the annual number of consecutive dry days in the mid-century will increase. Changes in annual number of consecutive dry days across SSPs range from 0.78 days (62% model agreement) to 1.5 days (75% model agreement)

- End-of-century: Across the domain, the majority of SSP scenarios project that the annual number of consecutive dry days in the end-of-century will increase. Changes in annual

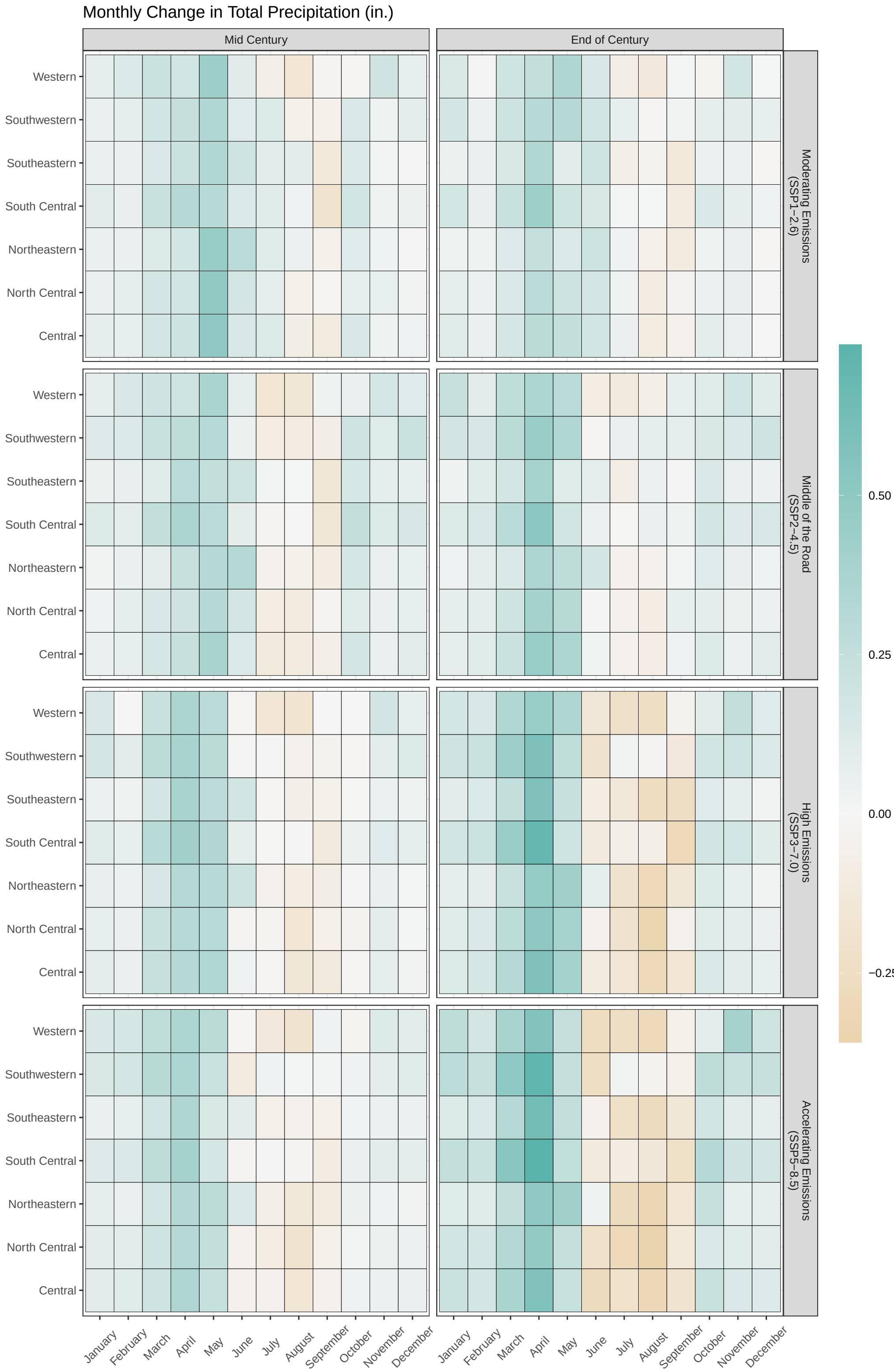

Figure 5.12: Projected monthly change in average precipitation (inches) for each Climate Division in Montana in the mid-century projections (2040-2069) for all SSP scenarios.

number of consecutive dry days across SSPs range from 1.3 days (62% model agreement) to 3.27 days (75% model agreement)

5.4.5 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 Figure 5.15 shows changes in projected number of wet days across Climate Divisions and domain-wide projections for mid- and end-of-century are given below:

- Mid-century: Across the domain, the majority of SSP scenarios project that the annual number of consecutive wet days in the mid-century will increase. Changes in annual number of consecutive wet days across SSPs range from 0.11 days (88% model agreement) to 0.13 days (100% model agreement)
- End-of-century: Across the domain, the majority of SSP scenarios project that the annual number of consecutive wet days in the end-of-century will increase. Changes in annual number of consecutive wet days across SSPs range from 0.12 days (100% model agreement) to 0.19 days (100% model agreement)

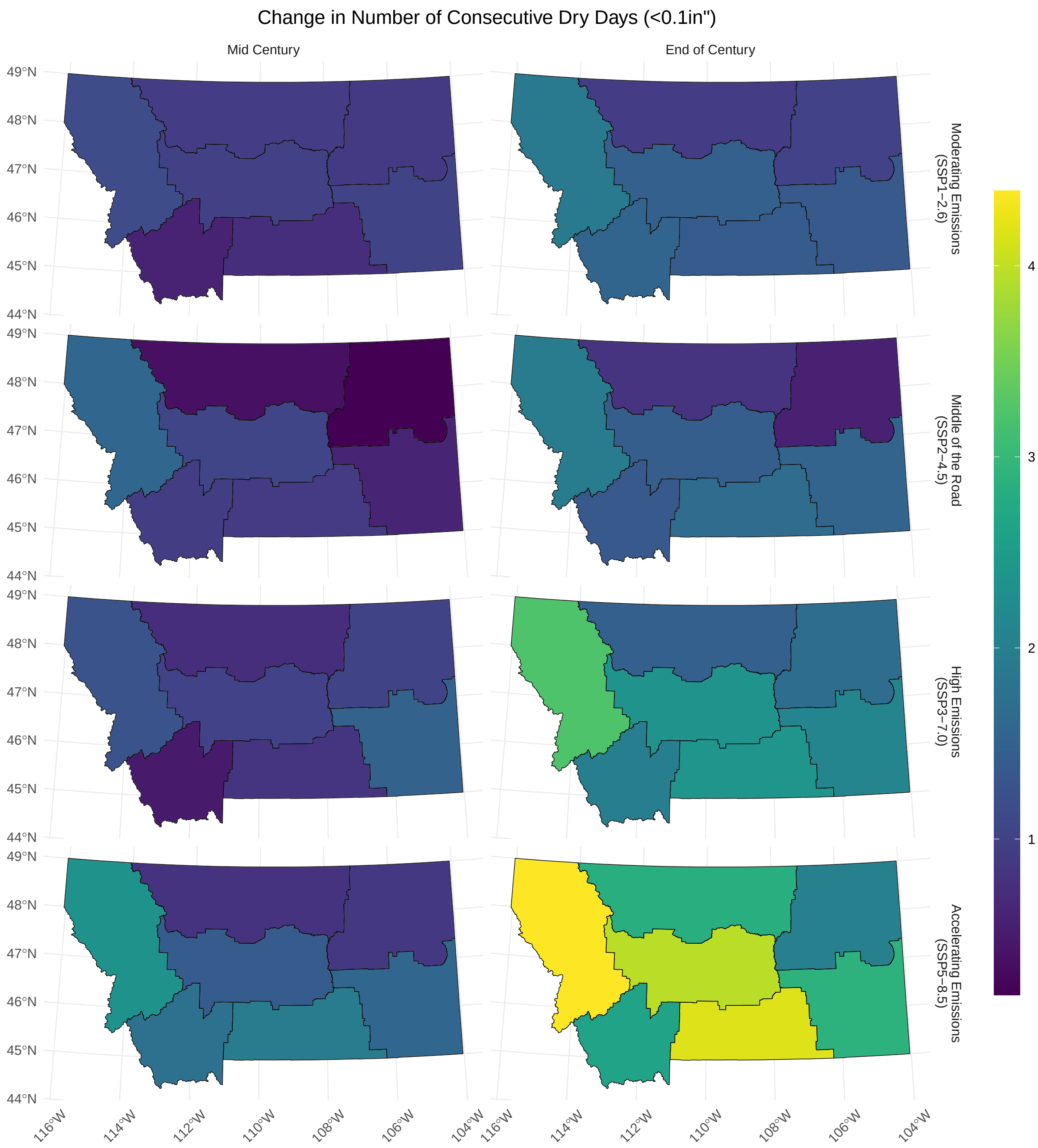

Figure 5.13: The projected change in the number of consecutive dry days (<0.1 inch [0.3 cm] of precipitation) for each Climate Division in Montana over two periods 2040-2069 and 2070-2099 for all SSP scenarios.

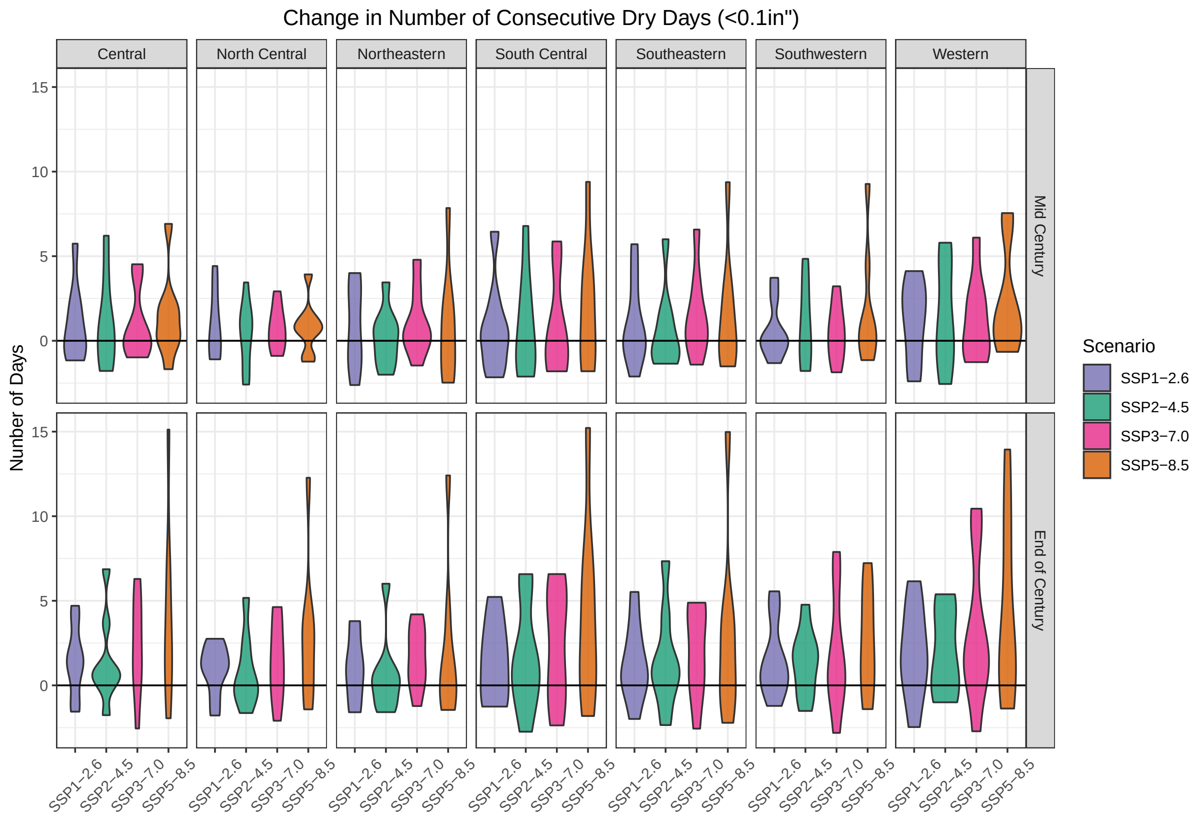

Figure 5.14: Graphs showing the number of consecutive dry days in a year projected for each Climate Division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099).

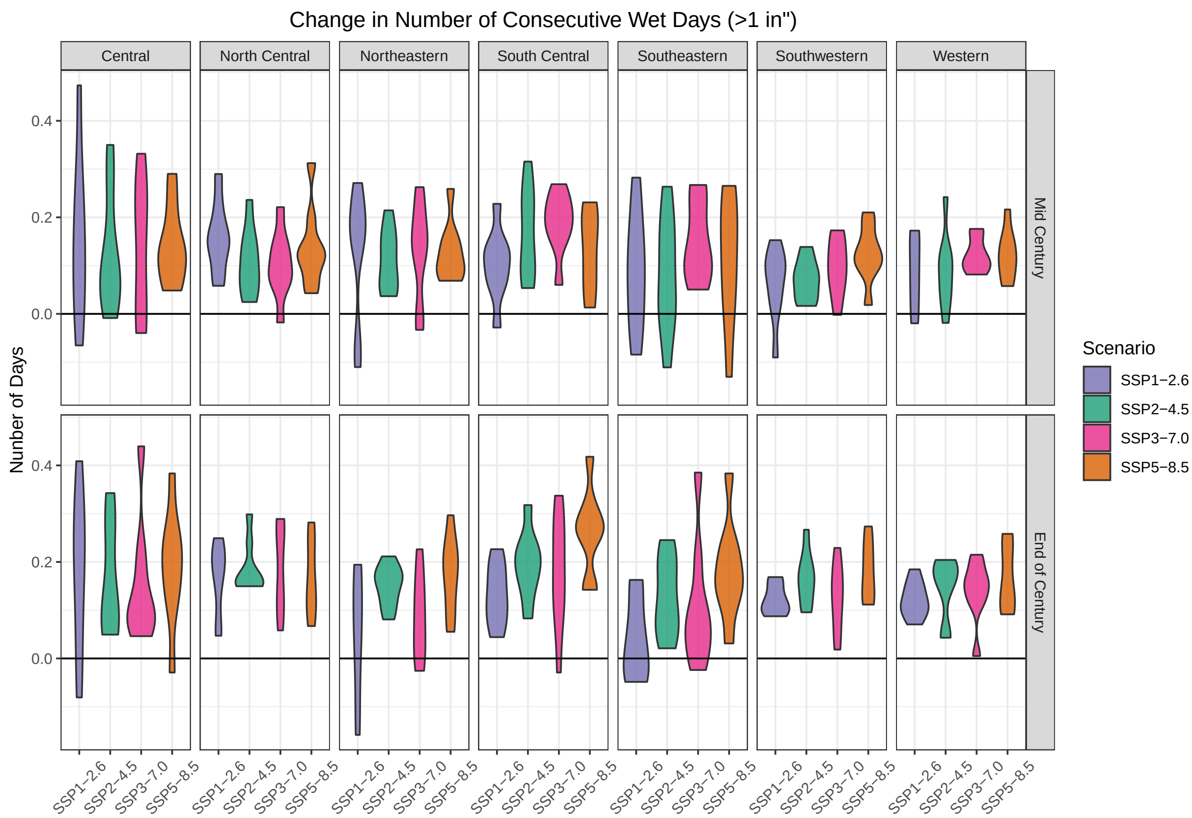

Figure 5.15: Graphs showing the increase in the number of wet days/yr projected for each Climate Division in all SSP scenarios. The top row shows projections for mid century (2040-2069) and the bottom row shows projections for end-of-century (2070-2099).

6 Draft 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.

7 Draft Conclusions

The analysis presented in this chapter shows that statewide, Montana has warmed—up to 1.9°F the between 1951 and 2015. Seasonally, that warming has been greatest in winter (3.2°F) and spring (3.5°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 1951 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 four shared socioeconomic pathways. Using those pathways, 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.

In Table 7.1 we provide a summary of the work done and described in this chapter. 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 5.5°F; by the end of the century, temperatures will increase by up to 9.2°F. Projections show that we could have up to 55 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 more then 60 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 slight increases in both dry and wet events.

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.

Table 7.1: 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 1951, average statewide temperatures have increased by 0.3°F/decade, with greatest warming in spring; projected to increase by 3-6°F by mid century, with greatest warming in summer and winter and in the east
Maximum Temperatures	Maximum temperatures have increased most in spring and are projected to increase 4-5°F by mid century.
Days above 90°F	Extreme heat days are projected to increase by 14-27 additional days by mid century, with greatest increases in the northeast and south.
Minimum Temperatures	Minimum temperatures are projected to increase 4-6°F by mid century.
Frost-free Days	Frost-free days are projected to increase by 22-32 days by mid century, particularly in the west.
Average Precipitation	Statewide precipitation has decreased in winter (0.15 inches/decade) since 1951, 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 (0.25-0.3 inches; a slight statewide decrease in summer precipitation and increased year-to-year variability of precipitation are projected, as well.

Climate Metric	Trend and Future Scenario
Number of Consecutive Dry Days	Projected changes range from 1.3 to 3.3 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	Slight increases across all climate divisions and SSP scenarios.

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