DRAFT Climate Change in Montana

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Draft Overview

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.

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.

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 **0.9 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.

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.

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 *southern* parts of the state.

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."

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.

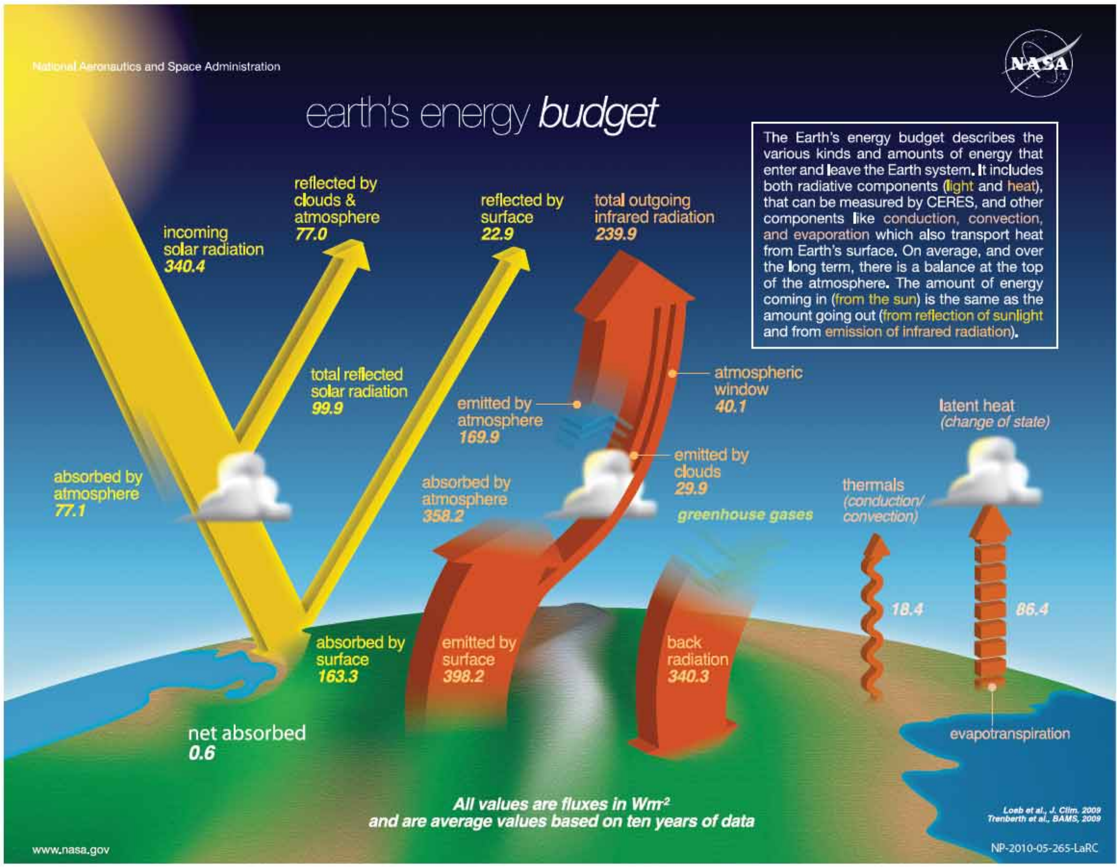

Figure 1.1: The Earth's radiation balance is the main driver of our climate. Image courtesy of National Aeronautics and Space Administration (NASA undated)

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 (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.

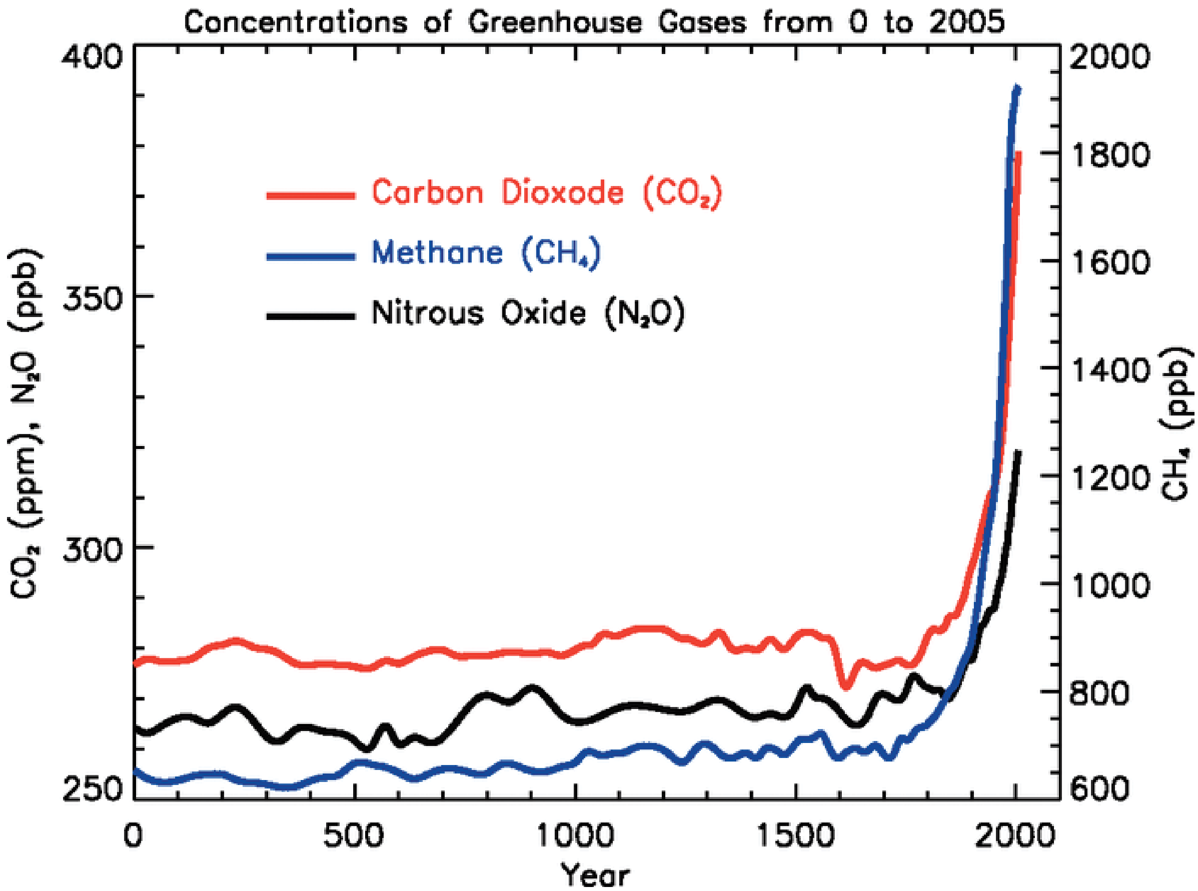

Figure 1.2: Changes in important global atmospheric greenhouse gas concentrations from year 0 to 2005 AD (ppm, ppb = parts per million and parts per billion, respectively) (Forster et al. 2007).

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 (CO2), methane (CH4), nitrous oxide (N2O), 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.

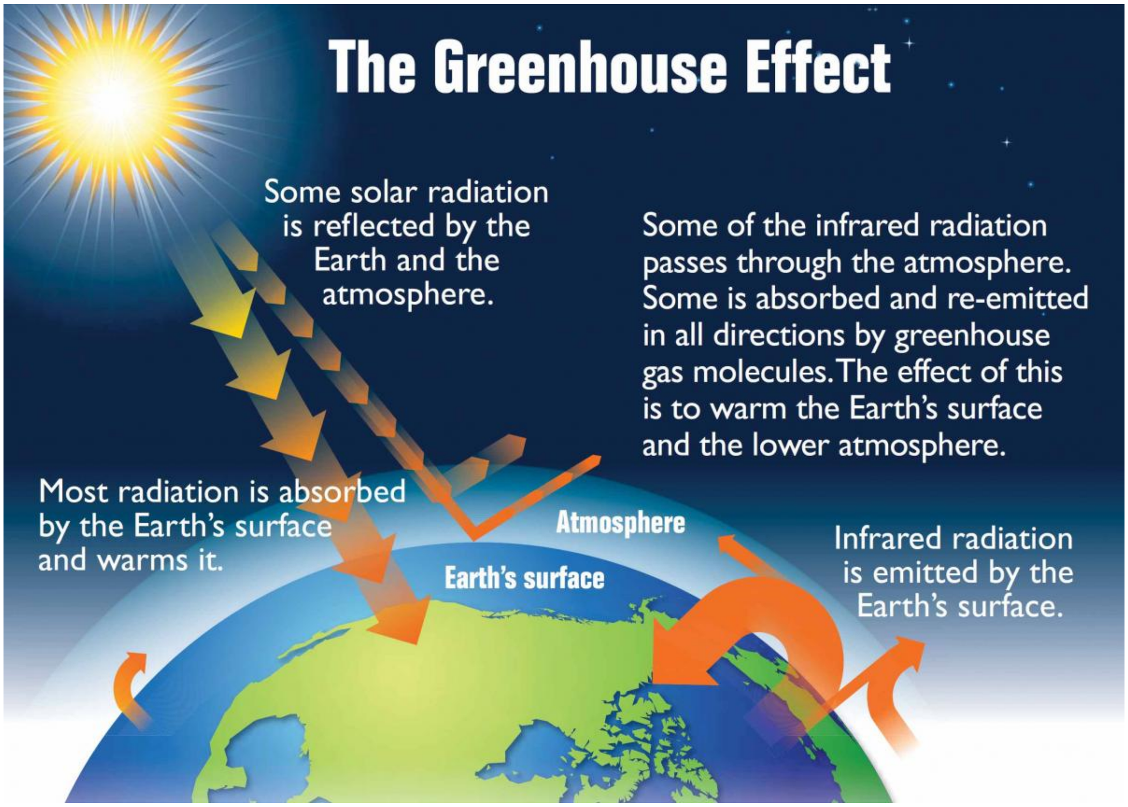

Figure 1.3: Climate change occurs when the Earth's energy budget is not in balance. Such change generally takes place over centuries and millennia. Human-caused climate change has been occurring over the last 200 yr, largely because of the combustion of fossil fuels and subsequent increase of atmospheric 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[1]. 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 (Figure 2-3) 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

Winters in Montana are cold, with statewide average temperatures of 25.7°F. 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 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 50.3°F, 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 51.9°F 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 61.9°F, temperatures generally peak in July and August, with mean daily highs above 90°F in the east, as well as in western valleys.

Fall temperatures in Montana are often highly variable, with an average temperature of 31.3°F. Days to weeks of warm temperatures are commonly followed by freezing temperatures that bring frosts and snow.

3.1.2 Precipitation

In general, Montana is a water-limited, semi-arid landscape where precipitation is depended upon heavily by plants and animals alike. Table 3.2 shows the seasonal variation of precipitation across Montana's 7 Climate Divisions 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 19.2. Western Montana typically receives twice as much precipitation annually as eastern Montana (31.9 in. versus 16.5 in., 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, a majority 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 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 1979 - 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 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.

The presentation of trends that follows is confined to the period from 1950–2015 using data from NOAA's NClimGrid Dataset (citation). 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).

3.2.1 Temperature

Table 3.3 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. 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 3.3: Decadal rate of change for annual average temperatures in °F (°C) for each region in the study area and statewide 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

Average annual temperatures increased for the entire state and within all climate divisions (see Figure 3.1). The rate of temperature increase was 0.3°F/decade across the state, and this rate was relatively constant across all climate divisions (Table 3.3). Similarly, average annual maximum and minimum temperatures increased statewide, and for all seven climate divisions, by 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 approximately 1.15°F and 1.02°F, respectively.

3.2.2 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 3.4. 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 3.4). 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

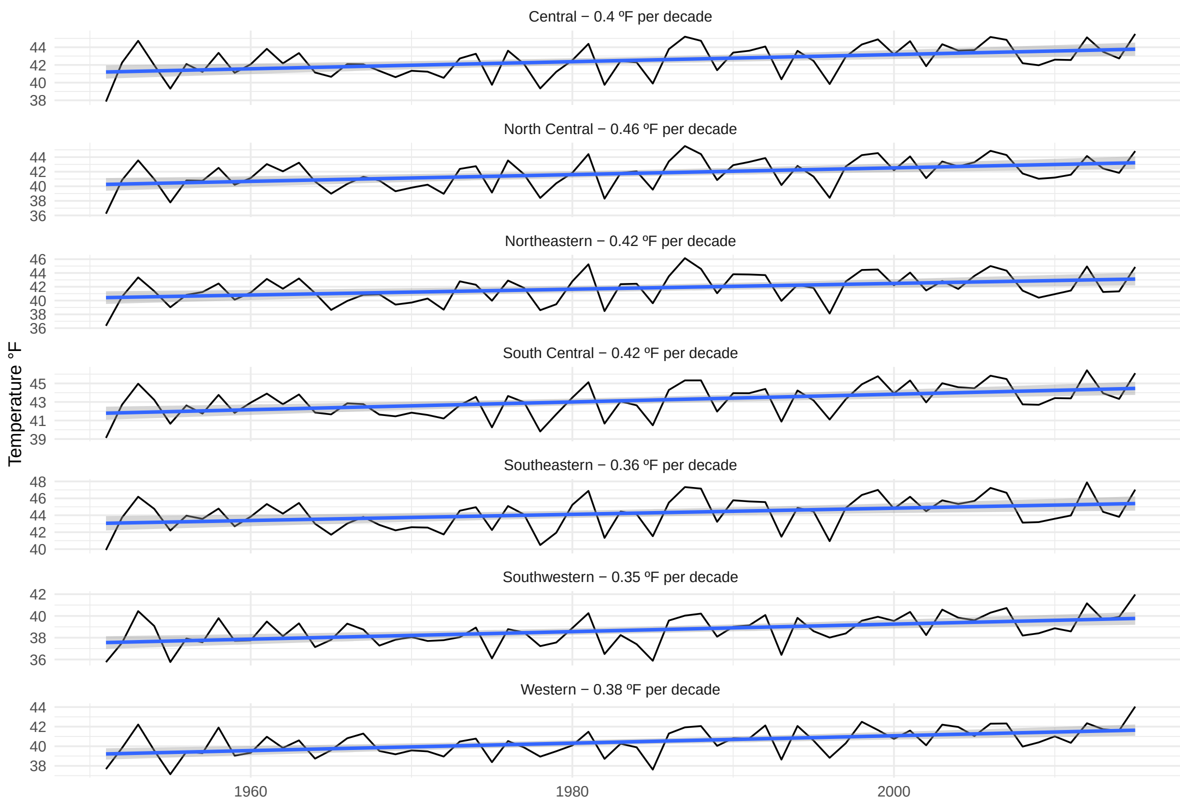

Figure 3.1: Trends in annual average temperature across each climate division (Figure I) in Montana

Montana's northwestern, north central, and central climate divisions. In the eastern portions of the state significant increases in precipitation have occurred during the spring months (Table 3.4).

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	Winter	Spring	Summer	Fall
Central	-0.12	0.08	0	0.06
North Central	-0.09	0.08	0	0.09
Northeastern	0.00	0.21	0	0.07
South Central	0.00	0.09	0	0.07
Southeastern	0.00	0.31	0	0.09
Southwestern	-0.13	0.09	0	0.07
Western	-0.56	0.00	0	0.00

3.2.3 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.

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.

4 Draft Future Projections

4.1 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 (Figure 4.1). 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.

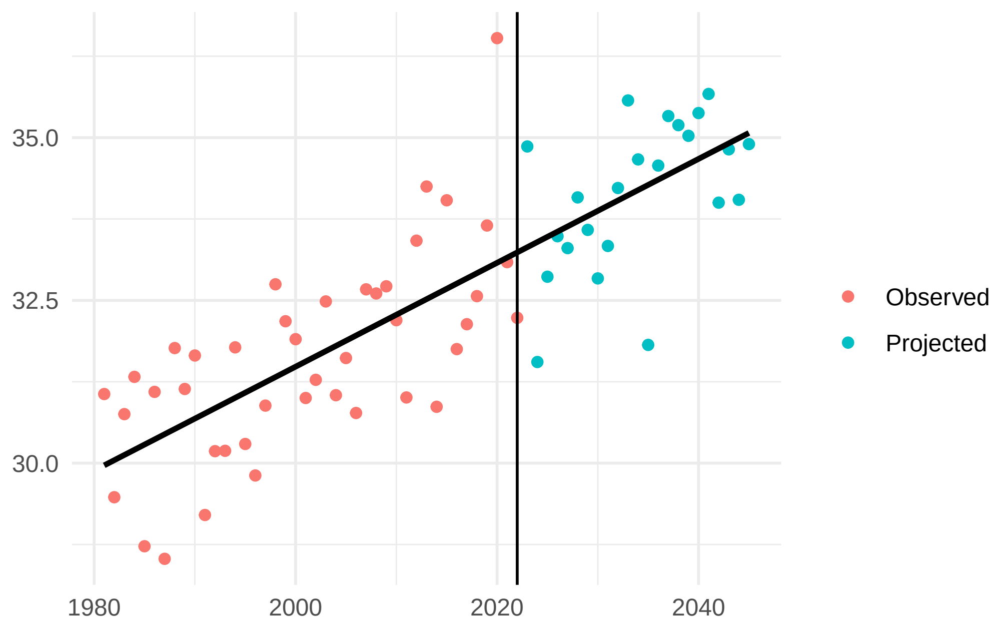

Figure 4.1: Example of fitting a linear model to data to predict future conditions.

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 (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/m2 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/m2. 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 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.

> Shared Socioeconomic Pathways
>
> **give overview of ssps**

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.

4.2 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.

4.2.1 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).

```
tmp_box_data <- normals::make_boxplot_data(
    stringr::str_subset(cmip_files, "tas.rds"),
    shp = shp,
```

```
    attr_id = params$attr_id
)

normals::make_boxplot_plot(
  tmp_box_data,
  "Temperature Change (°F)",
  "Change in Mean Annual Temperature"
)
```

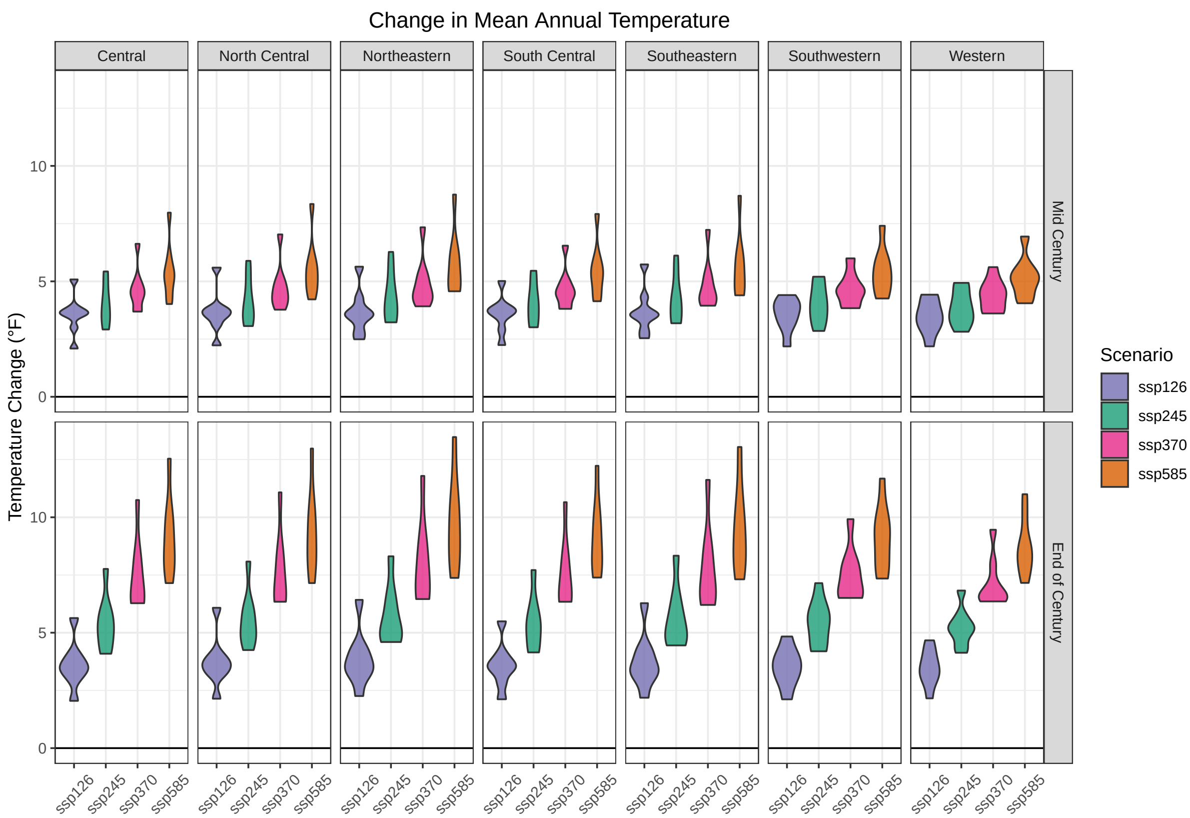

Figure 4.2: Graphs showing the minimum, maximum, and median temperature increases (°F) projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century (2040-2069) projections and the bottom row shows end-of-century (2070-2099) 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%.

4.2.2 Average Daiily 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%).

4.2.3 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.

4.2.4 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).

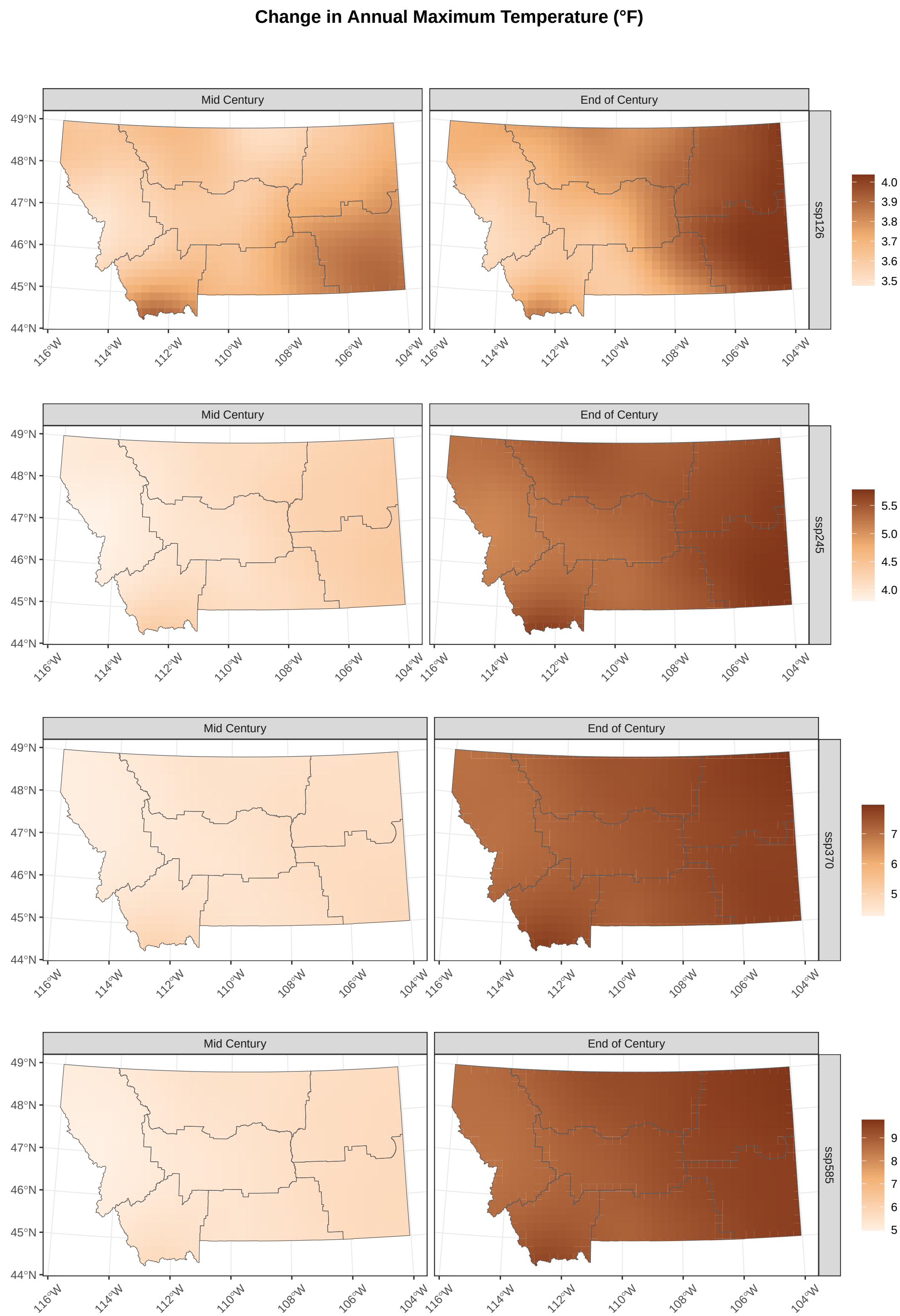

Figure 4.3: The projected increase in annual average daily maximum temperature (°F) for each climate division in Montana for the periods 2049-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

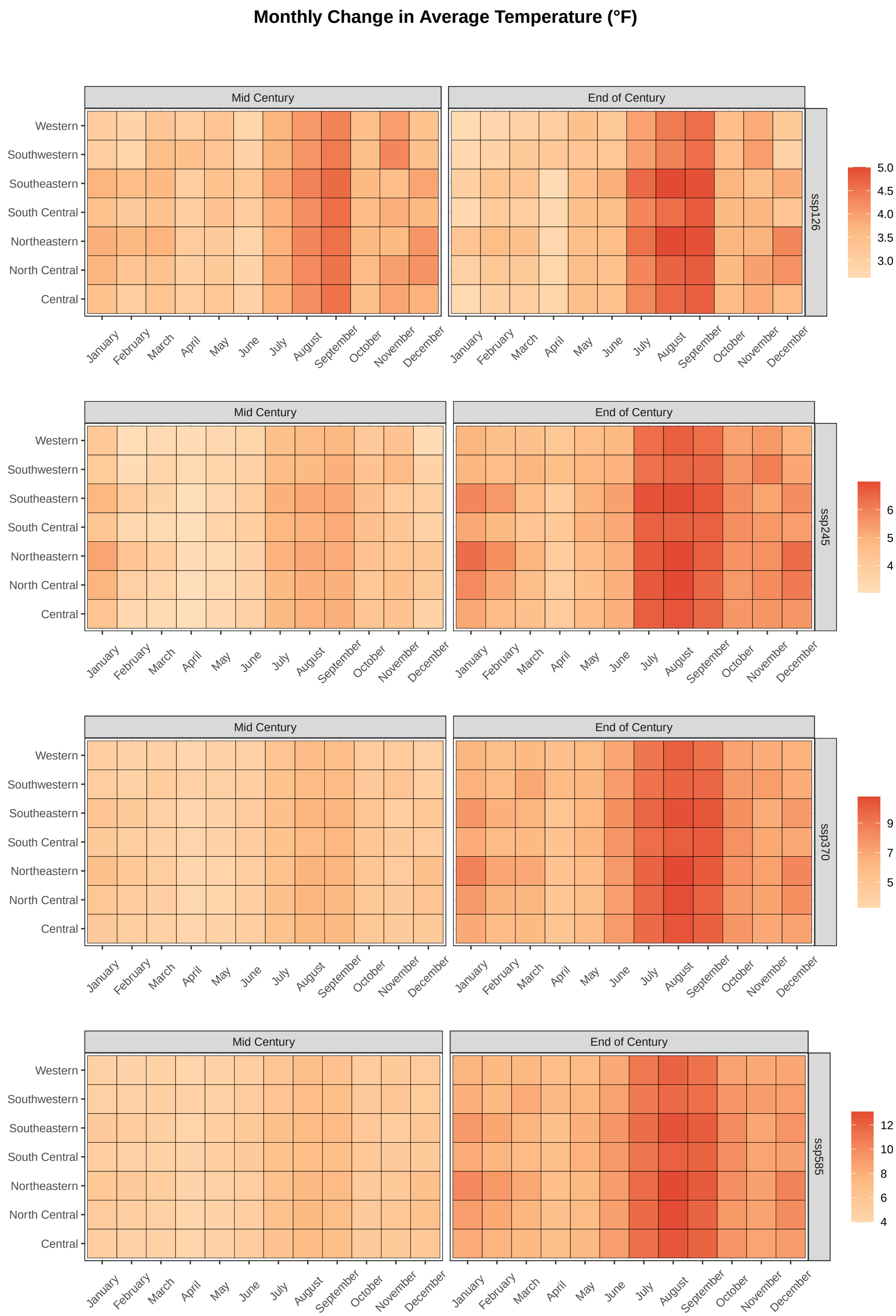

Figure 4.4: The projected monthly increase in average temperature (°F) for each climate division in Montana in the mid-century projections (2040-2069) for the (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

- 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%).

4.2.5 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.

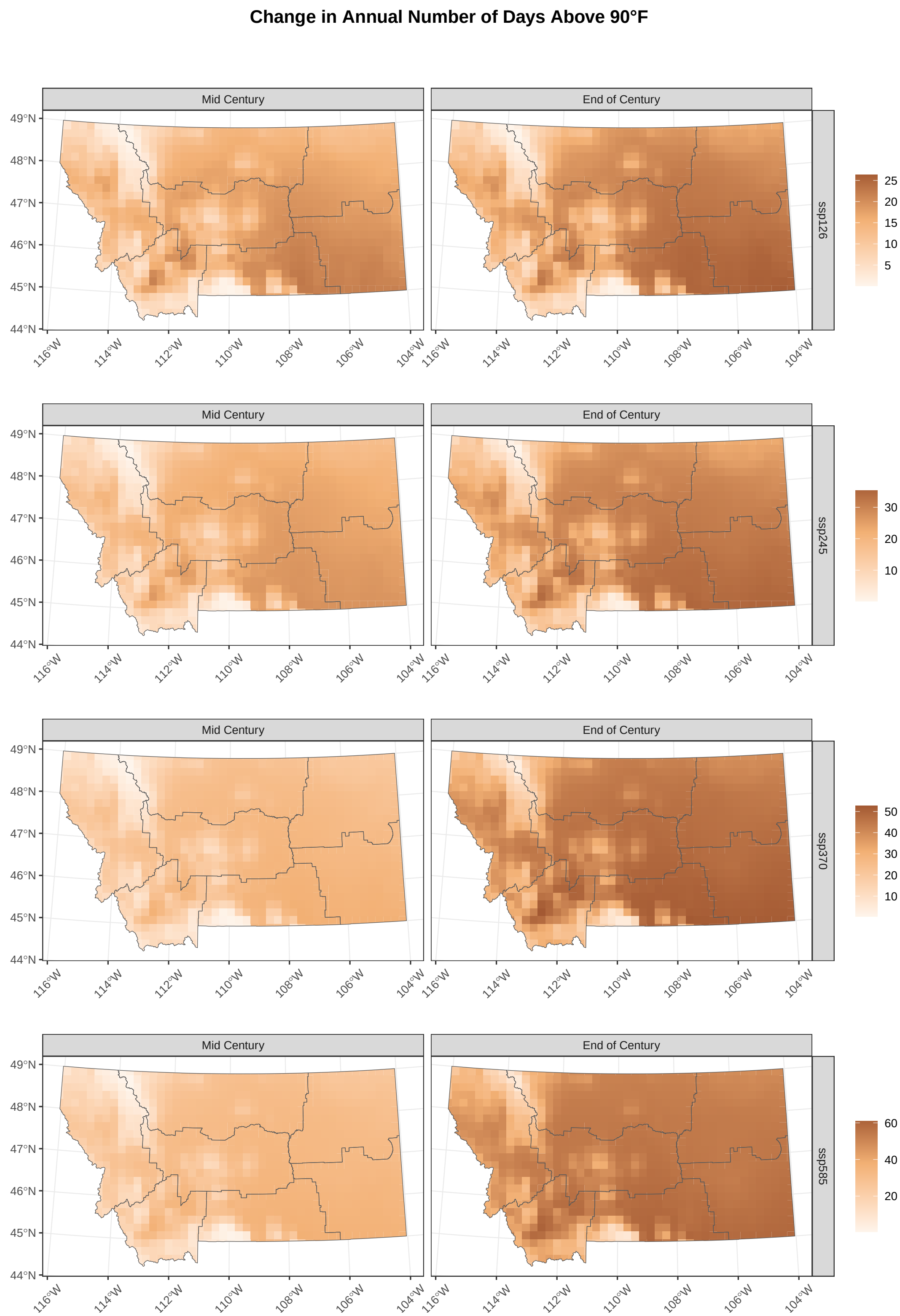

Figure 4.5: The projected increases in number of days above 90°F (32°C) for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

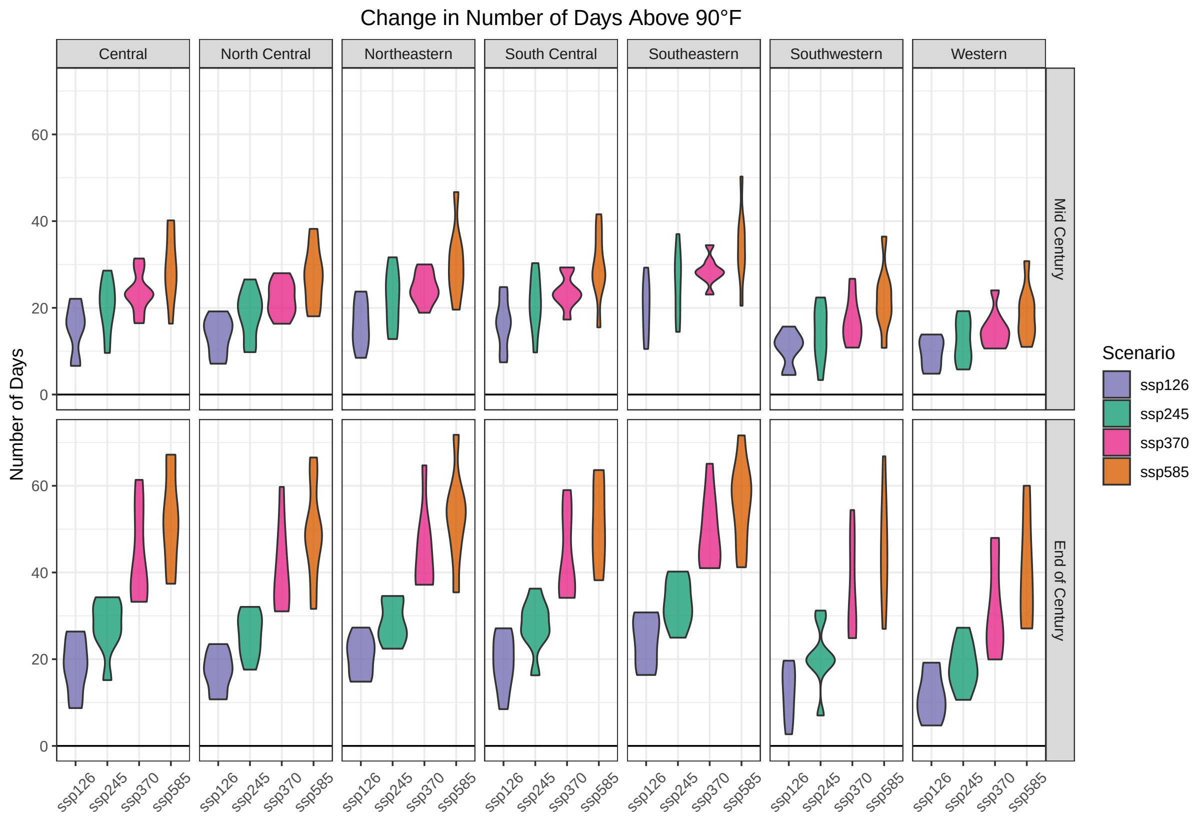

Figure 4.6: Graphs showing the increase in the number of days per year above 90°F (32°C) projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century 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%.

- 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%).

4.2.6 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.

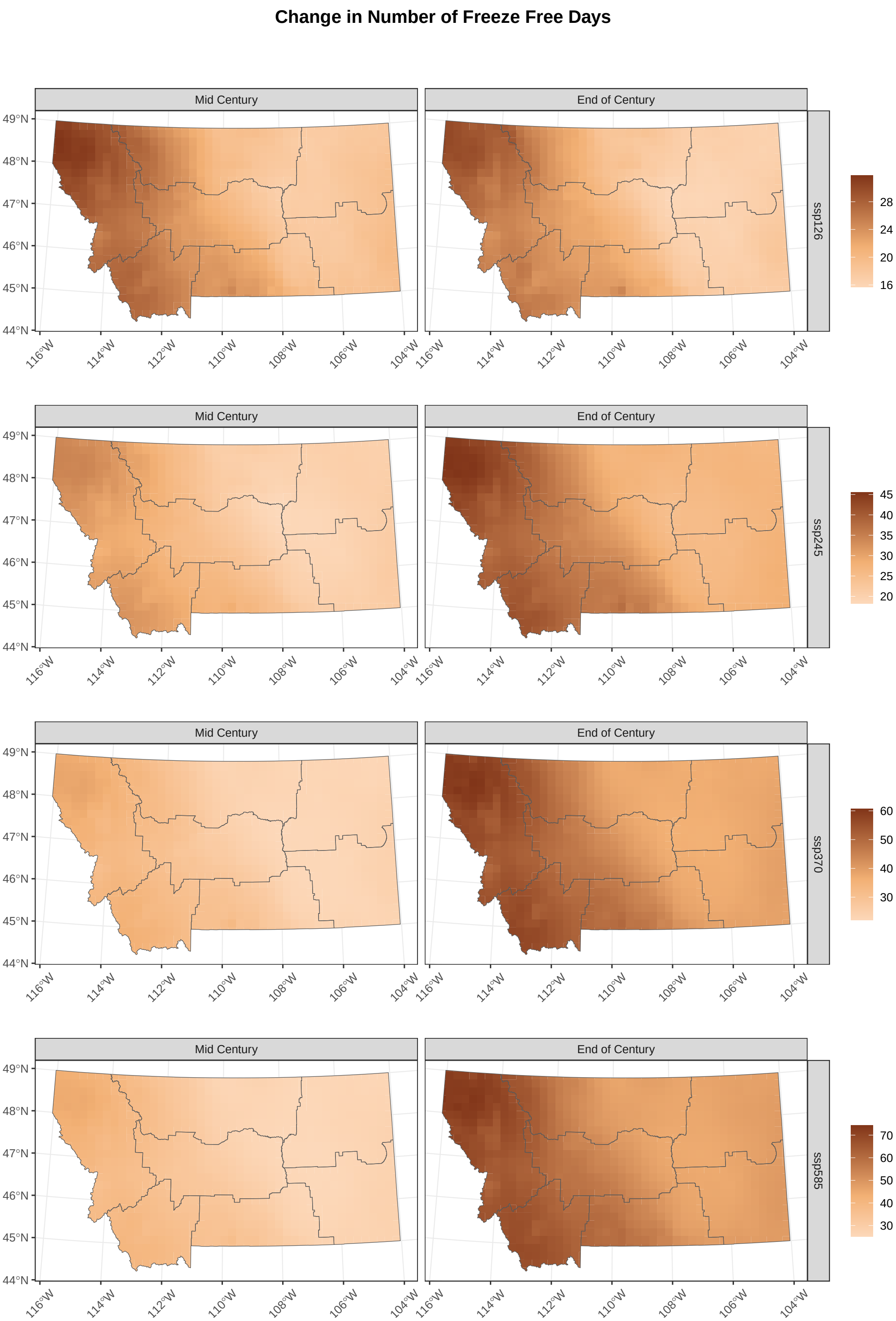

Figure 4.7: The projected change in the number of frost-free days for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

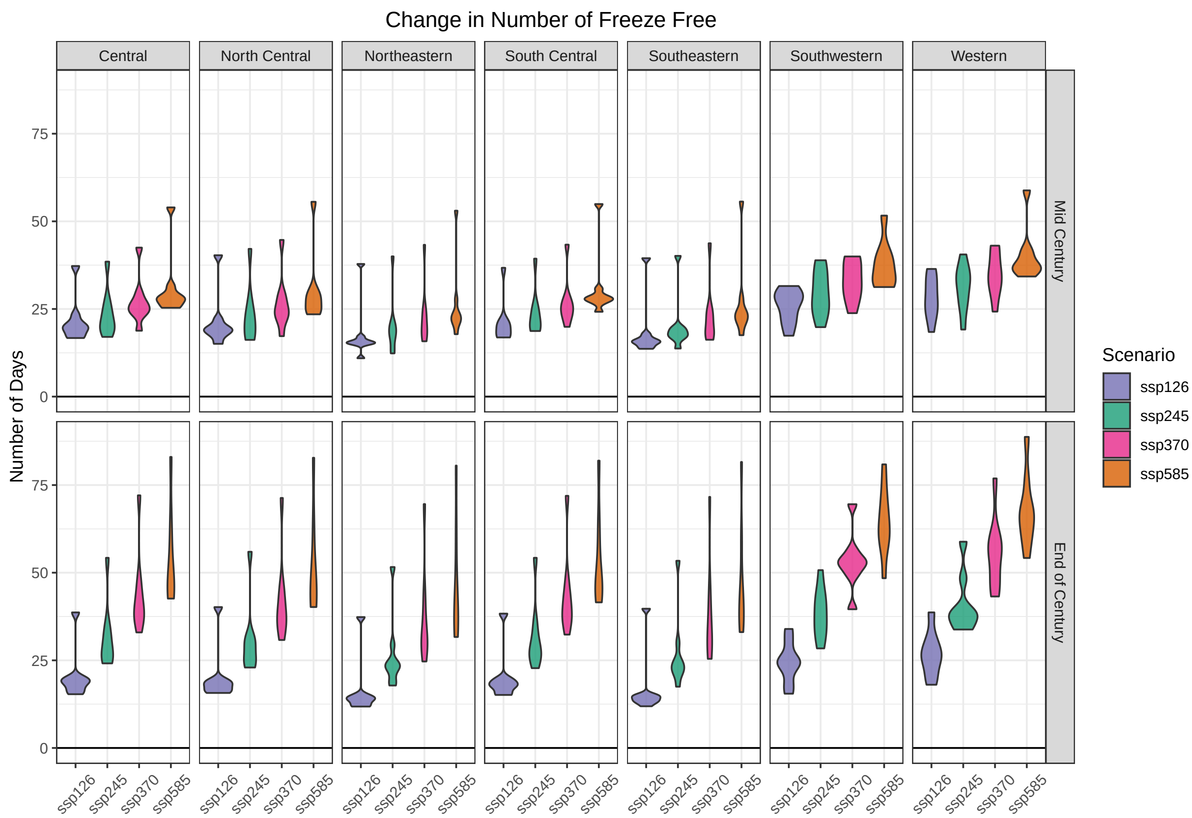

Figure 4.8: Graphs showing the increases in frost-free days/yr projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). The 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%.

4.3 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.

4.3.1 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/yr) 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%).

4.3.2 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.

4.3.3 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.

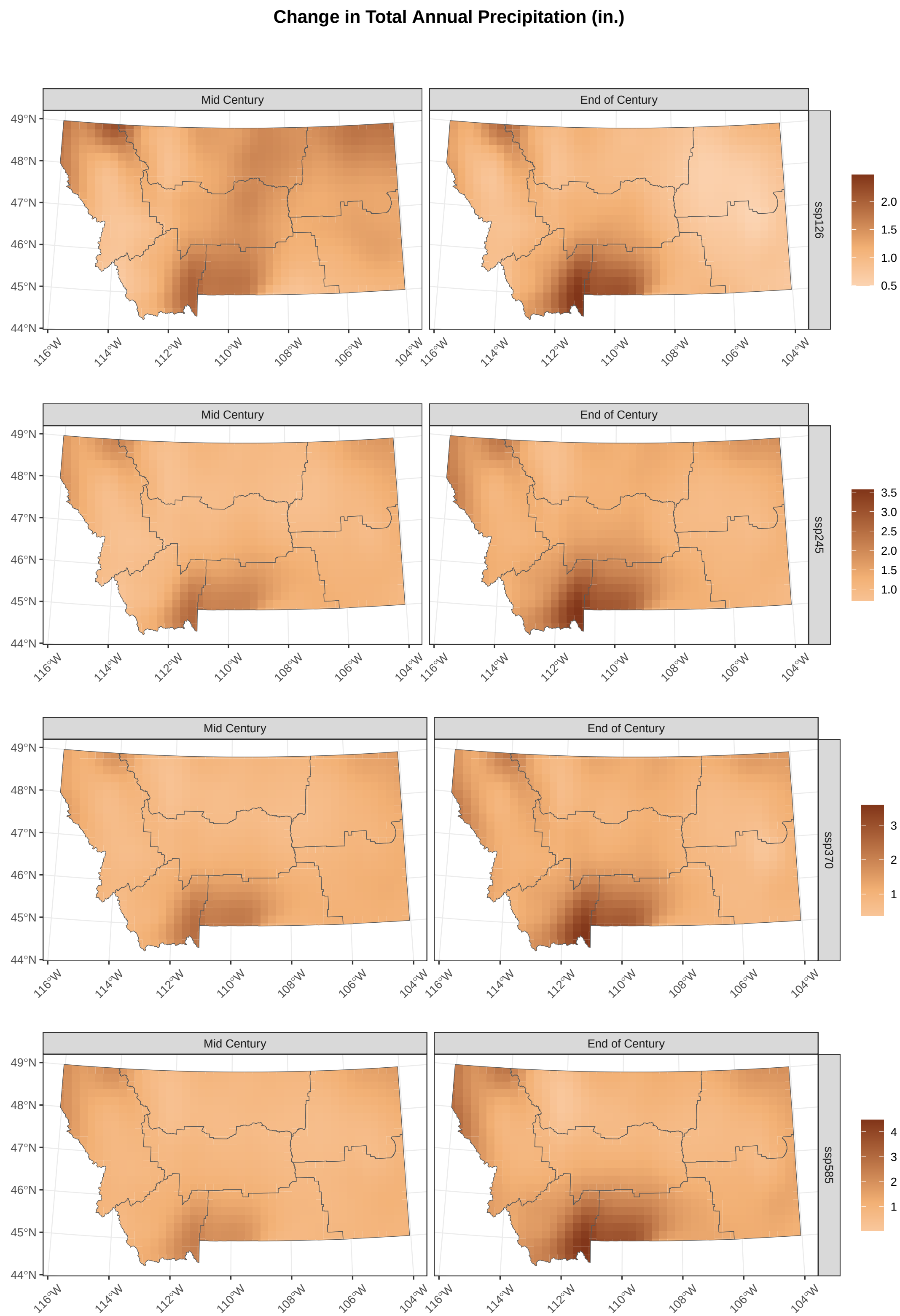

Figure 4.9: The projected change in annual precipitation (inches) for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

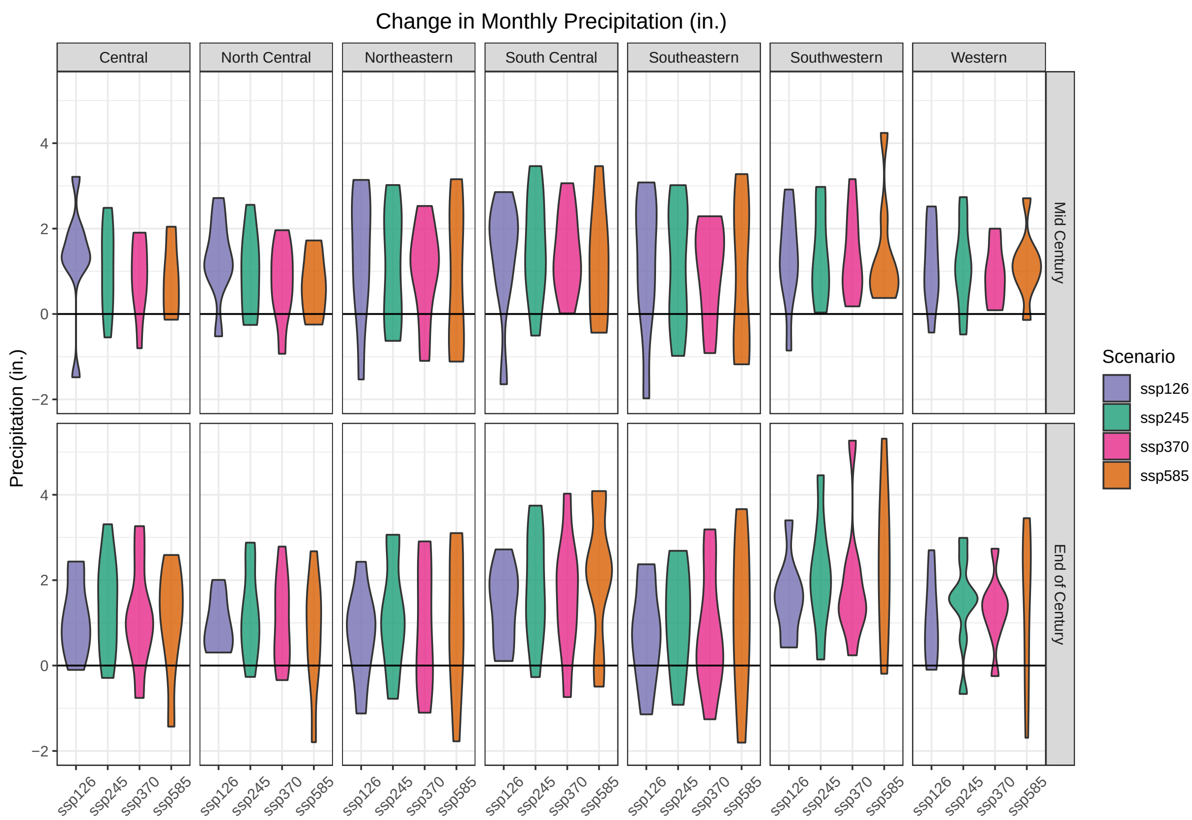

Figure 4.10: Graphs showing annual precipitation change (in inches) projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). 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%.

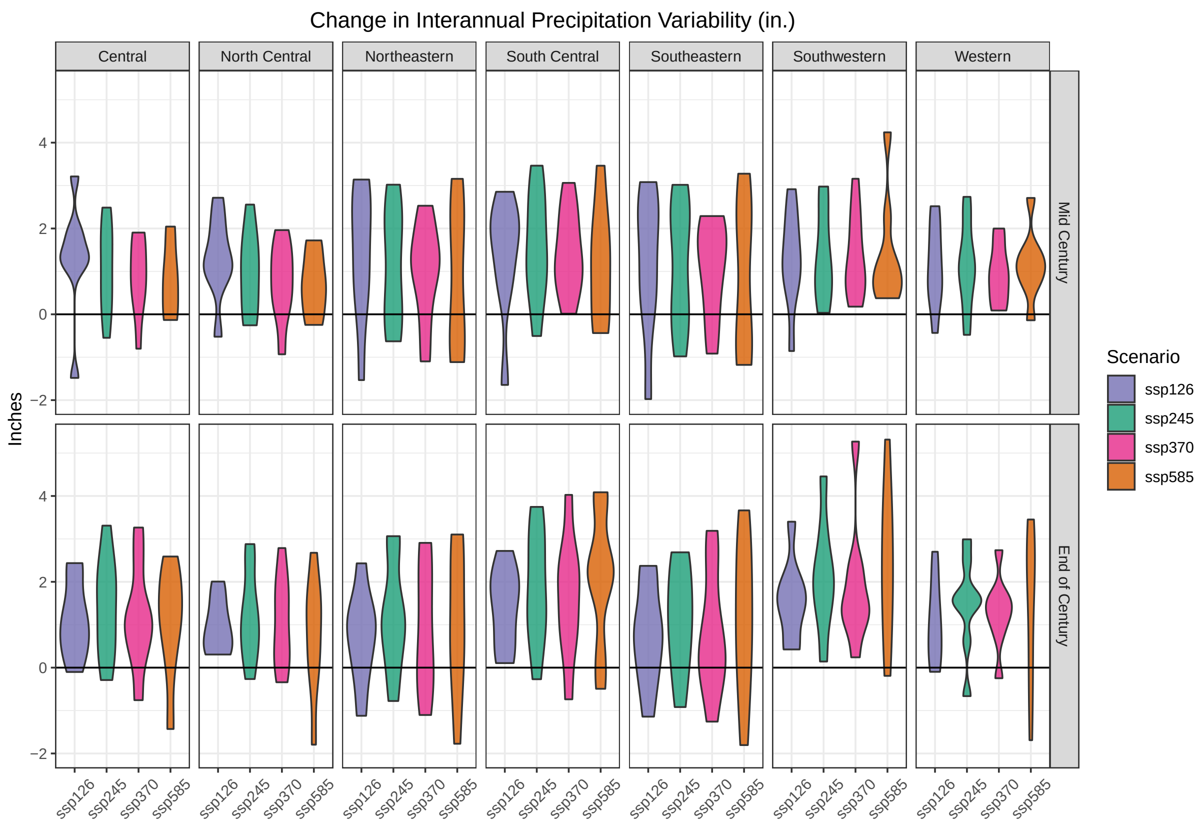

Figure 4.11: Graphs showing the interannual variability of precipitation projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows for end-of-century projections (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.

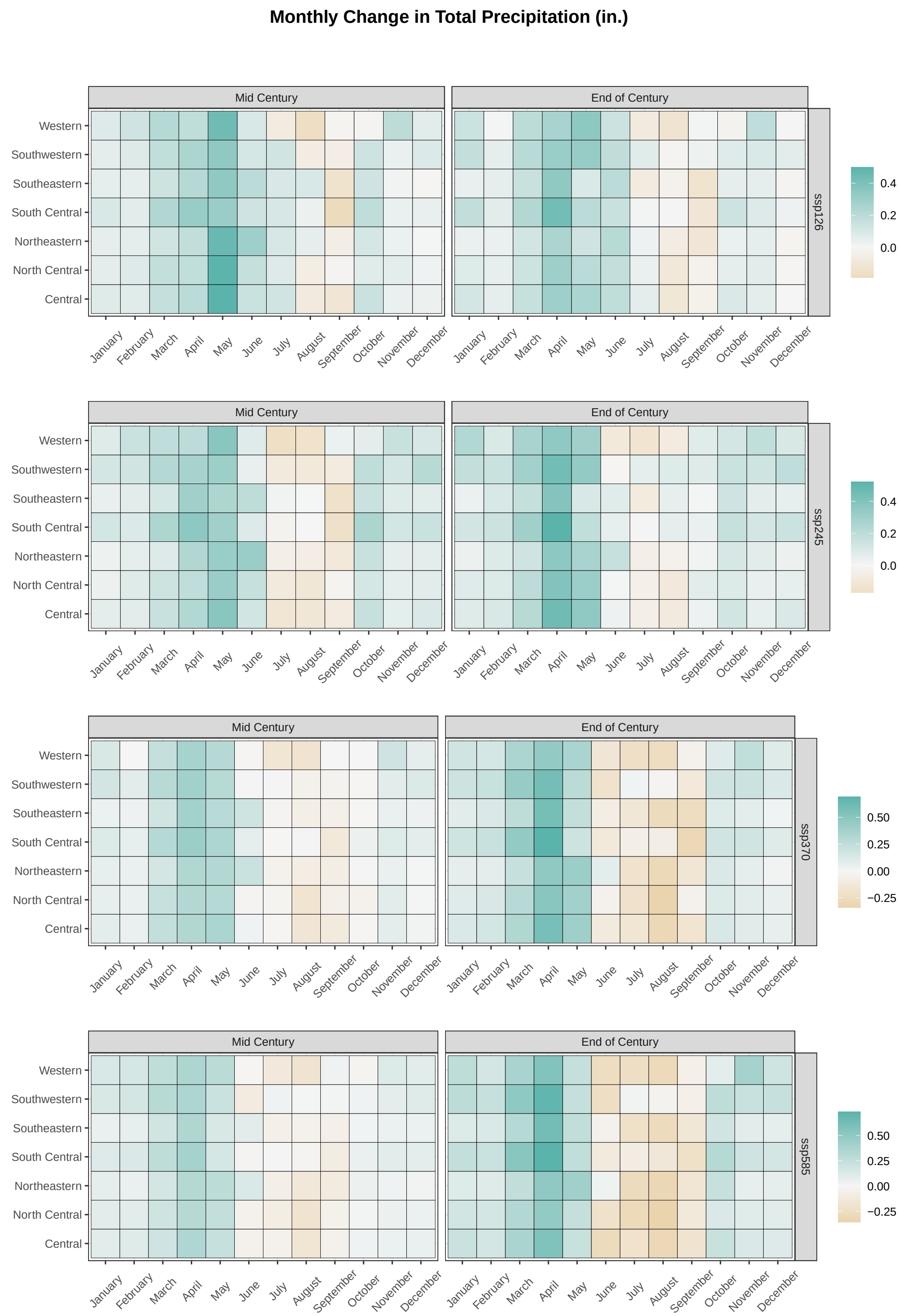

Figure 4.12: Projected monthly change in average precipitation (inches) for each climate division in Montana in the mid-century projections (2040-2069) for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

- 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%).
- 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%).

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. 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.

4.4.1 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.

4.4.2 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.

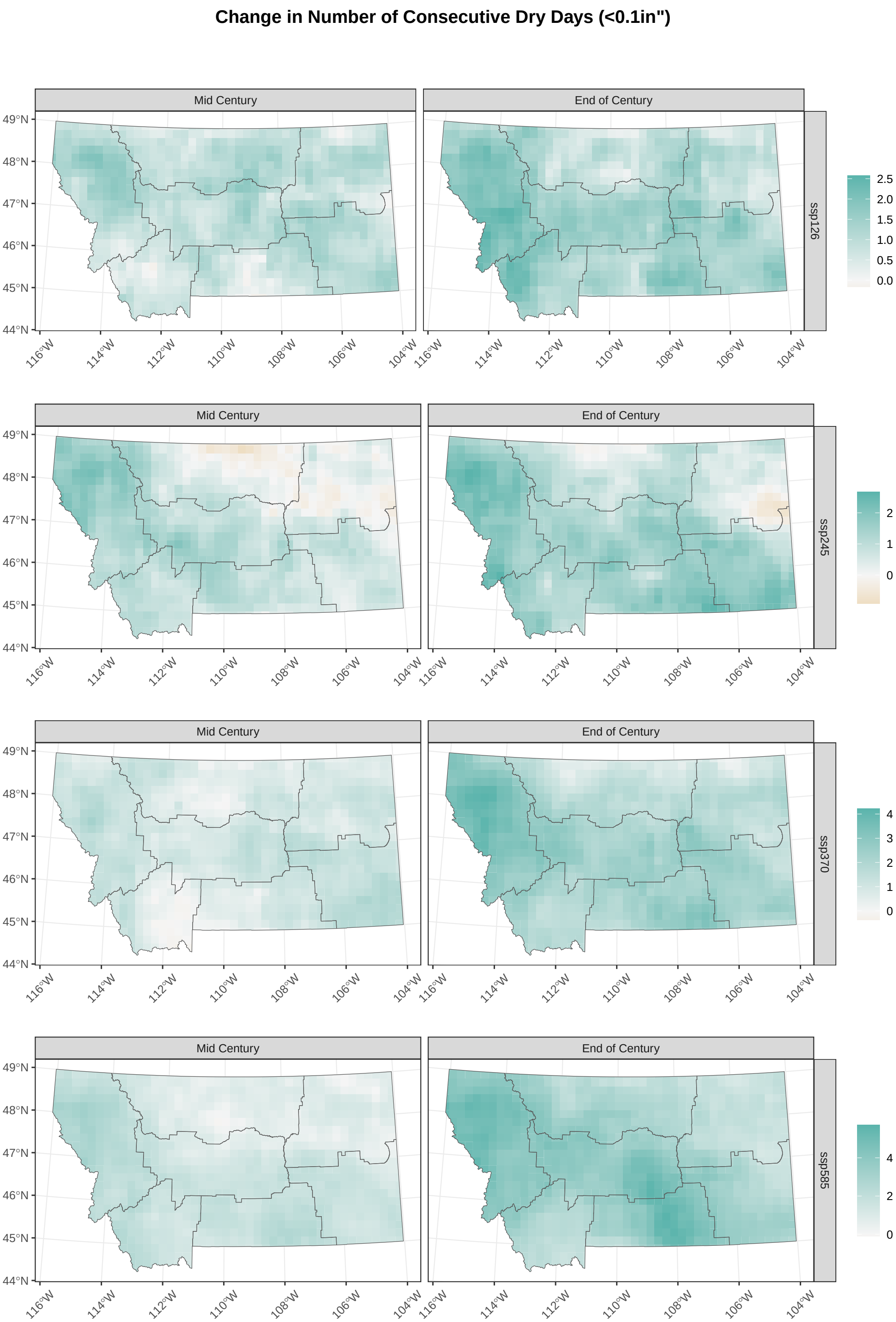

Figure 4.13: The projected change in the number of consecutive dry days (<0.1 inch [0.3 cm] of precipitation) for each climate division in Montana over two periods 2040-2069 and 2070-2099 for (A) stabilization (RCP4.5) and (B) business-as-usual (RCP8.5) emission scenarios.

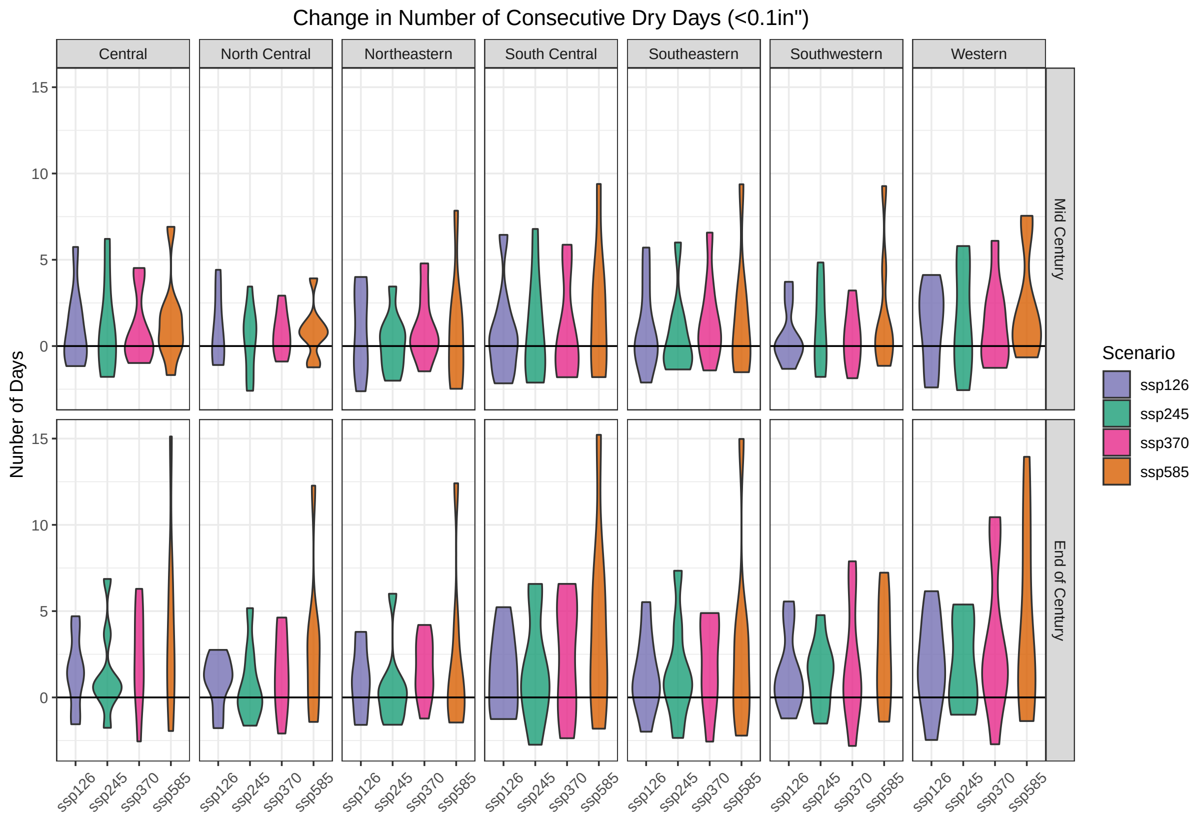

Figure 4.14: Graphs showing the number of consecutive dry days in a year projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows mid-century projections (2040-2069) and the bottom row shows end-of-century projections (2070-2099). 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.

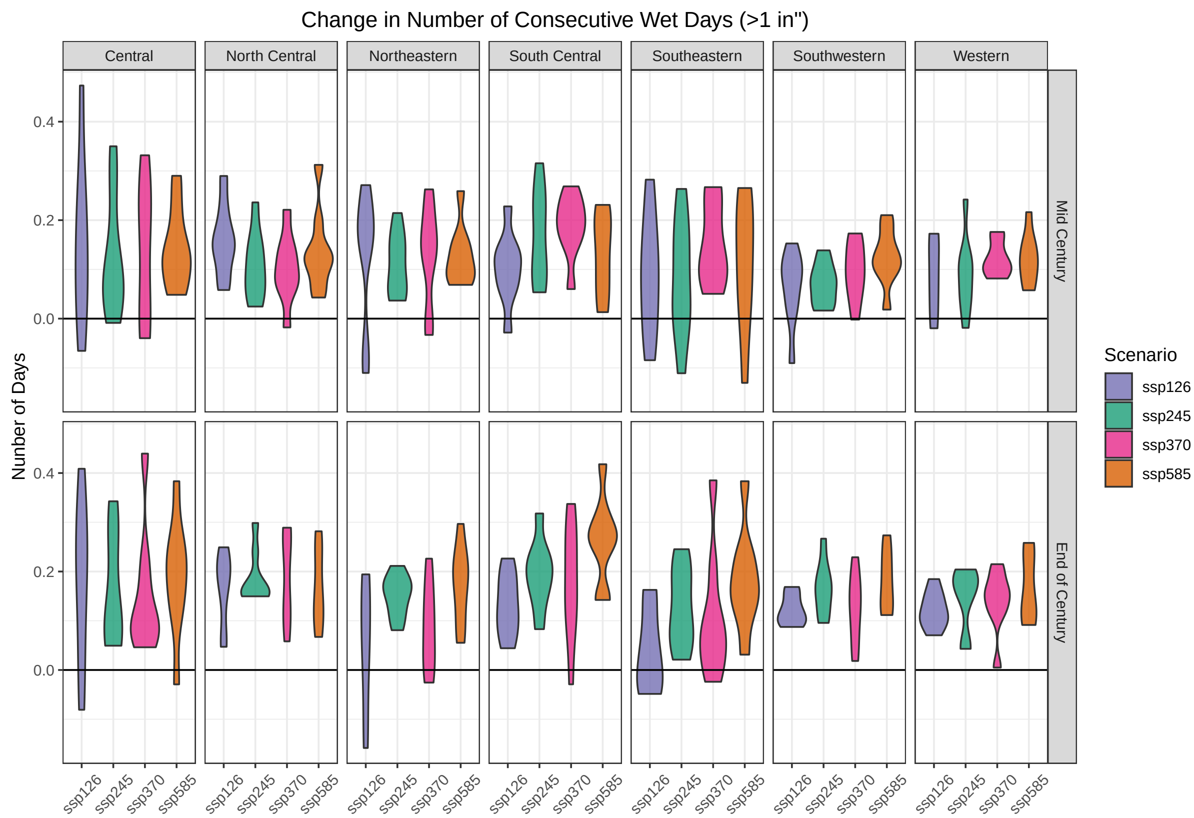

Figure 4.15: Graphs showing the increase in the number of wet days/yr projected for each climate division in both stabilization (RCP4.5) and business-as-usual (RCP8.5) emission scenarios. The top row shows projections for mid century (2040-2069) and the bottom row shows projections for end-of-century (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.

5 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.

6 Draft 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.

Summary Table

References

1. Abatzoglou, J. T. Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology* **33**, 121–131 (2013).